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ABSTRACT

This volume provides a guide to management of utilities metering in educational facilities, especially colleges and universities. Chapter 1 gives an overview of why utility measurement, specifically the metering of energy consumption, is important in facilities management. Chapter 2 defines the basic units of measurement for both electric and nonelectric energy, defines the common multipliers that describe the magnitude of a measurement, and discusses basic utility rate structures and their impact on energy costs. Chapter 3 considers the fundamental elements and components of utility metering how alternative current is measured, common types of analog metering, present-day digital technology, and performance metering. Chapter 4 describes metering products that are currently available, such as nonintrusive appliance-load monitoring systems, electric metering networks, and main electric meters. Chapter 5 discusses management aspects of the role of metering in a deregulated environment, including strategies to reduce electric energy costs, energy management plans, and meter specifications and installation. An appendix provides basic statistical information for managers and information on measurement reliability. (Contains 36 references.) (DB)

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The Metering Guide for Managers

By Mohammad H. Qayoumi, Ph.D., P.E.

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Preface

In the summer of 1996, as part of an Electric Power Research Institute (EPRI) design team, I participated in developing the outline for *Educational Facility Guidebook: Innovative Electric Solutions* for electric utility account representatives who work with educational institutions. As the discussion on the outline continued, it became obvious that lack of adequate utility metering is one of the key barriers for effective energy management for most organizations. This is how the idea for writing a publication on metering and measurement got started. In the meantime, as deregulation of electricity moved from a concept to implementation in a few states, the need for better and more reliable metering became more evident.

As we began to develop the topics for this book, it became obvious that writing a book that only discussed new metering technologies would not be very useful for most readers. So, we decided to investigate how data from utility meters must be an integrated element of the enterprise-wide information system. In other words, it was essential that we find the linkages between metering data and organizational needs. That is why the first chapter of this book discusses basic management aspects of measurement and how energy information ties in as a part of a bigger picture. Moreover, since a general knowledge of statistics and reliability can assist in acquiring valuable insights in data analysis, several appendices on these topics were added.

Many organizations collect large quantities of data; in other words, the natural propensity of most institutions is to drown themselves in data, yet starve in wisdom. The hope of this book is, on the one hand, to avoid metering complexity that will be unhelpful, and on the other hand, to prevent oversimplification that may result in misleading information. A large number of facilities managers can tell you exactly how they measure and collect utility consumption data. However, if you subsequently ask them how they integrate energy information with institutional goals and objectives, most of their responses become very fuzzy.

The motivation behind this book is to investigate how energy data interplay into overall operational costs and to seek ways to creatively interrelate energy data with institutional priorities. More specifically the book addresses the following points:

- How do we identify, measure, and collect energy data that support organizational goals and objectives?
- How can we maintain some level of predictability and control over future energy costs in view of the deregulation of electricity?
- How do we balance the amount of energy information required to make timely decisions and metering system costs?
- How can we determine the appropriate technologies and level of metering required?
- How can we develop a measurement system where such basic principles of continuous quality improvement as the Malcolm Baldrige National Quality Award (MBNQA) core values are incorporated?
- How can we design a metering system that meets both the day-to-day operational needs and the strategic requirements of the organization's decision support system?
- How can we create a metering system that promotes energy efficiency and operational effectiveness?

If we look at the electrical industry, especially in the deregulated environment, we see a complex web of interdependencies among several entities: power generators, transmitters, power pools, local distribution companies, and the utility customer. The metering technology available today can successfully provide the infrastructure to rise above the challenges ahead, provided it is viewed in the larger context of organizational performance. In other words, by looking at the 11 core values and concepts identified by MBNQA, we can identify the following measurement factors:

- continuous improvement and learning
- fast response
- design quality and prevention
- partnership development
- result focus

In his book, *Reframing Organizations,* Lee G. Bolman presents four models that signify important aspects of every organization:

- *Structural Frame*—describing the rational aspects of an organization
- *Human Resources Frame*—defining the relationship between an organization and human nature
- *Political Frame*—knowing the political realities in negotiating choices for effective management
- *Symbolic Frame*—recognizing the power of symbols and culture in shaping organizational performance

Bolman demonstrates that viewing an organization in less than all four dimensions falls short of developing insights for effective solutions. In applying the above concept to energy measurement and metering, it becomes clear that some facilities managers are effective in approaching this problem only in the structural model; many facilities managers may feel this is sufficient. This tendency may explain that although energy cost is sizable for many organizations, most senior administrators do not appreciate the role of energy measurement and its implications. This is because facilities managers have not articulated their issues successfully in the other three suggested frames.

The movement of this book from idea to publication through the partnering of EPRI, the International Facility Management Association (IFMA), and APPA: The Association of Higher Education Facilities Officers, is symbolically significant to the message it conveys. In the deregulated environment, partnership and cooperation are critical among the electric utility customers, the local electric utility, the transmission utility, the power pools, and the independent power generators.

Probably because I've had 22 years' experience in higher education administration, many of my examples are based on campuses of buildings serving higher education. Nevertheless, the principles of metering and measurement presented in this book apply to any set of buildings serving education, government, or corporate missions.

I sincerely hope this book meets the needs and expectations of its most important customers, namely the readers of the book. May you always be able to measure what is important and use the information to continuously improve your operations.

With Kindest Regards

Mohammad H. Qayoumi

chapter one

Overview

Organizations depend on measurement and analysis of performance. Measurements are driven from institutional strategy and provide critical insights about core processes, outputs, and results. The types of data needed for performance measurement and improvement include customer service, cost, operational efficiency, effectiveness, and staff satisfaction.

Measurement is a means and not an end. Measurement facilitates extracting larger meaning from data to support evaluation and decision making at all levels of an organization. Data analysis can help determine both trends and root causes, making it an integral part of planning, reviewing, and improving any campus operation. In short, a measurement system is an integral part of a decision support system.

This chapter gives an overview of the reasons measurement is important in facilities management. It specifically addresses measuring energy consumption and discusses why metering has suddenly attracted more attention in managing facilities than ever before. Although the energy intensity of the U.S. economy (defined as the total energy consumed divided by the gross domestic product) has dropped for the past three decades, energy consumption for buildings has steadily increased. In 1970, building energy consumption in the United States was 22 quadrillion British thermal units (quads) while today the figure has risen to over 30 quads. Thus building energy use constitutes a large and growing share of national energy consumption. In addition, the deregulation of electricity is changing energy market forces in fundamental ways. The main reasons for this heightened interest in metering include

- increasing pressure for cost containment
- changing government rules
- changing markets resulting from electricity deregulation

Public Pressures for Cost Containment

Public pressure for cost containment is increasing, and measurement has become an important issue in both government and

higher education. The cost of attending college has become a major issue in the eyes of the public, lawmakers, and the press. Many policymakers are examining how the rising costs of college limit access to many sectors of the society. According to *USA Today*, tuition rates at Harvard, the University of Chicago, Carleton, and Duke grew 4.6 percent faster than the annual rate of inflation from 1977 to 1992. Although fee increases for public universities have not been as dramatic, the issue has still been the subject of scrutiny by the U.S. Congress, state legislatures, the press, and the public. According to a *Newsweek* survey of parents with children under the age of 4, when asked about their greatest fear in raising their children, 52 percent of parents cited worry about the cost of education, 35 percent cited health care, and 22 percent cited the cost of day care.

In its final report published in 1997, the National Commission on the Cost of Higher Education stated that colleges risk "an erosion of public trust" if their charges continue to escalate. Moreover, if colleges and universities do not behave responsibly and bring costs under control, others will do it for them. Finally, Dr. C. Peter Magrath, president of the National Association of State Universities and Land-Grant Colleges, in a letter to its members, indicated that one of the most troubling challenges facing higher education today is "the college cost issue." He stated that "we must continue to work on controlling costs while aggressively working to address faculty and administrative productivity."

Responding to these pressures, some universities have begun to reduce tuition or to keep tuition flat for several years. Controlling energy costs can help balance the upward cost pressures in other areas where the task of cost control is even more challenging.

A second potential cost pressure for universities comes from technological breakthroughs in telecommunication, which have made distance education a major topic of discussion. The creation of virtual universities in cyberspace, the offering of college credits on the Internet, and the Western Governors Initiative has fueled the discourse. Although distance education has been used for a number of years, its use was relatively limited. Operating and maintaining campus facilities cost roughly between 7 and 10 percent of the total university budget in addition to significant

capital costs. The energy and utilities cost can significantly contribute to this amount. Since virtual universities would not be burdened with this cost, they have a structural cost advantage when compared with traditional universities.

Government Rules on Grants and Contracts

Universities and other research organizations are under pressure to increase their sponsored research activity. This is happening at a time when the government has significantly reduced appropriations in this area. For instance, the nondefense research and development budget for 1995 was roughly $34 billion. However, the appropriation was dropped to around $28 billion for 1996 and has remained flat with no hope of any notable increase for the near future. The *Wall Street Journal* reports that during the past decade, major U.S. high-tech companies have also slashed their research and development expenditures.

While competing for fewer research dollars, these research organizations are also being asked to forego part if not all of the research overhead costs, namely the facilities energy and maintenance costs and administrative support. As illustrated by the new Office of Management and Budget (OMB) Rule 20, there has been a major effort by federal government funding agencies to move away from reimbursing all facilities costs and instead, to develop new rules and standard rates for facilities charges. If a university or other research group has very energy-inefficient buildings, it will end up subsidizing a larger part of the research cost since it will not be able to receive full reimbursement for space costs.

Electric Utility Deregulation Also Drives New Metering Needs

The advent of electric utility deregulation brings new challenges and opportunities for facilities managers of colleges, universities, and other campus environments. Any owner of multiple buildings is an important commercial customer to whom utilities are beginning to pay close attention. Also, acquiring electrical service in a deregulated environment will likely be more complex. In the current structure, electric utilities are typically single vertical monopolies. In a deregulated environment, customers will interact with two or three distinct entities: a generation company, a transmission company, and a distribution company.

What Is Regulated and What Is Not?

The 3,300 electric utilities in the Untied States are a $250 billion industry that includes investor-owned electric utilities (IOEU), public power agencies, cooperatives, and municipalities. Impending deregulation will fundamentally change the relationship of these utilities with their customers. Deregulation of electricity deals primarily with generation. A facility or campus will still receive electricity through the distribution network of its local utility. Relationships with local utilities are transformed in that the customer must choose to purchase power from the utility or use them as a path to receive electricity from another provider. Depending on individual state regulations, the utility may also have the right to sell many new services, including metering.

Purchasing electricity in an open market environment requires that an informed customer be able to analyze market conditions and assess the needs of the institution so as to lower the overall cost of electricity. Deregulation can be viewed as a double-edged sword. *Organizations who prepare adequately for deregulation will reap dividends. Those who are not prepared could end up paying much higher prices for electricity, creating more cost pressures on their institutions.*

One of the underlying reasons the price of electricity fluctuates over time is that it cannot be economically stored in any appreciable quantities. Generation and consumption of electricity have to match at every instant in time. However, the need for electricity changes daily and seasonally. For instance, the need for electricity is much higher at noon than at midnight at most campuses and is higher in the summer overall because of air-conditioning loads.

Capital cost is more than two-thirds of the cost of electricity. When a generation unit is constructed, there is a strong financial motivation to have the unit operate continually, except for periodic maintenance shutdowns. If a unit operates only for a small portion of the day or the year, the cost of electricity from that unit will be much higher on a per-unit basis.

In order to reflect varying costs due to varying usages, utilities have instituted tariffs or "rates" where the cost of electricity is higher during peak hours and peak seasons. Some utilities have tariffs where the cost of on-peak power is two to three times higher than off-peak power. In a deregulated environment, price

differences between on-peak and off-peak may be even greater. For instance, due to the high summer temperatures in July 1998, high power demand for air-conditioning, and unusually constrained capacity in the Chicago area, electricity traded briskly at $7.60 per kilowatt-hour to bulk power purchasers. The typical cost of electricity is 3.9 cents per kilowatt-hour at that time of the year. Dramatic price fluctuations could become the norm rather than the exception in a deregulated environment.

In order to prepare for a deregulated market, organizations need to spend more time and effort to learn how much electricity they use, at what time, and where. They must also learn whether it is possible to shift loads or change power demands without an appreciably negative impact on operations. Relevant and reliable consumption data are required to determine load profiles. Consumption data are collected with metering. Unfortunately, most organizations do not have either adequate or well-maintained metering. In many cases, there is only the main electric utility meter and no branch meters to indicate how much energy is used in different parts of the campus. Where used, branch meters are often not properly sized. Moreover, lack of calibration and maintenance result in "meter drift," which means the reading may not be reliable. Finally, even if a campus has properly sized and well-maintained meters, these units may all be electromechanical meters where data cannot be remotely read and processed for easily developing load profiles. In reality, lack of a good metering system is the principal barrier that will prevent many organizations from taking advantage of utility cost reduction opportunities.

The importance of metering in a deregulated environment is well illustrated by recent events in Europe. In 1990, the United Kingdom began opening electric markets to retail competition. By the end of 1998, 23 million small commercial and residential consumers were able to chose their power supplier. Currently, the Electricity Pool of England and Wales prices electricity by the half hour. This provides opportunities for power marketers to offer a variety of different on-peak and off-peak rates. Customers may bundle loads together to take advantage of special rates. However, customers must know their individual load profiles and the quantities of power needed each hour of the day. This information is communicated to energy suppliers daily for the following day.

The Role of Submetering

Determining load profiles, identifying major energy users, and defining consumption patterns are the first steps in bringing energy costs under control. This is the prerequisite to uncover opportunities for savings. Submetering is the means to obtain data for trend analysis and to determine consumption profiles of major load centers. The main reasons for submetering are as follows:

- to determine the cost of individual facilities objectively rather than by pro rata allocation,
- to account for energy costs by every department or cost center,
- to monitor the efficiency of large equipment such as chillers, boilers, and compressors,
- to provide valuable data for evaluating energy conservation projects,
- to identify performance problems and guide preventive maintenance, and
- to verify savings from energy conservation projects.

With reliable profiles for campus major loads, there are many opportunities for a campus of buildings to reduce the cost of electricity well *in advance* of deregulation. These may include modifying load shapes by changing the schedules of certain loads, equipment duty cycling, or installing thermal energy storage to reduce peak demand.

Real-Time Pricing and Load Shape Modification

One of the more innovative techniques available in some regions of the United States is real-time pricing (RTP). Real-time pricing tariffs have also been offered by power providers in Australia, Canada, New Zealand, Norway, and the United Kingdom for commercial and industrial customers for a number of years. More than 30 U.S. utilities—including Pacific Gas & Electric, Southern California Edison, Long Island Lighting, Duke Power, Georgia Power, and Baltimore Gas & Electric—have made RTP available to their customers. If campus or building energy use remains at status quo, neither the utility nor the customer realizes a benefit. However, if customers reduce energy consumption

during high energy use or peak periods, they may realize significant dollar savings.

State utility commissions are watching RTP offerings with great interest. Many commissioners believe this approach can have a positive effect on the successful implementation of retail wheeling. According to an article published in *EPRI Journal* (March/April 1997), the Marriott Marquis at the World Financial Center in New York City has been saving more than $100,000 annually using RTP techniques without any negative impact on its operations.

Therefore, it is fair to say that metering and energy measurement will begin to play a far more central role in operating facilities. Before discussing various types of metering, their capabilities, and the technologies behind them in later chapters, it is important to define the role of facilities managers in the metering process and to identify the purpose for installing meters at your specific campus.

Once the purpose of metering is agreed upon, a measurement plan can then be developed. The measurement plan should identify data to be collected, all locations for data monitoring, and frequency of data collection. Finally, a detailed data acquisition and analysis plan is needed.

Before proceeding to these more detailed plans, however, it might also be helpful to explain the role of the facilities manager and some basic concepts that can be used for measuring energy. These explanations will help managers develop the conceptual framework needed to articulate the need for metering in alignment with organizational goals and objectives.

Management Aspects of Measurement

Lord Kalvin over a century ago commented:

> "When you can measure what you are speaking about and express it in numbers, you know something about it; and when you can not measure it, you can not express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you are scarcely in your thought advanced to the stage of a science."

Measurement serves as a self-assessment tool to determine where an organization is, where it wants to go, and how far along

it is in attaining its goals. Measurement is a continuous improvement vehicle that reduces process variation, identifies problems and trends, determines process efficiency and effectiveness, or assesses opportunities for process improvement. In other words, measurement is an integral part of a decision support system. Measurement provides insights that are not obvious and provides the infrastructure for fact-based decisions (Table 1.1).

Although there is a general agreement that measurement is an important factor for continuous organizational improvement, it is equally critical to underline the motivation for it. Measurement can be viewed both as a language of progress and as a means to determine steady advancement toward goals and objectives. Moreover, it can serve as an effective communication tool within an organization. Finally, measurement influences performance and can be a strong behavioral tool. In the words of Eli Goldratt, "Tell me how I am going to be measured, and I will tell you how I am going to behave."

Therefore, as we begin to measure certain parameters, it is essential to know what subtle messages are communicated as well as to understand possible unintended consequences of the measuring. Individuals might concentrate on measures to maximize perceived performance in one direction at the cost of suboptimizing the overall system. The challenge is to develop a set of measures that will truly reflect the current conditions, safeguard against suboptimization, and serve as an incentive for continuous improvement.

Table 1.1 Management Aspects of Measurement

Energy Communication Tool	Energy Planning Tool	Behavioral-Modification Tool
■ Check utility rates ■ Identify possible operations and maintenance problems ■ Set reliability and power quality level goals	■ Allocate energy costs accurately across buildings and cost centers ■ Determine energy improvement opportunities ■ Size new equipment or meters properly ■ Evaluate prior energy improvement projects	■ Conserve energy ■ Improved system efficiency ■ Shed load ■ Reward and recognize systems related to energy improvement initiatives

Attributes of Good Metrics and Measurement Systems

A good set of measurements must reflect both customers' needs and organizational strategies or objectives. One commonly deployed framework for a good measurement system is the "balanced scorecard" developed by Robert S. Kaplan and David P. Norton. The balanced scorecard consists of the following four perspectives:

- **Financial Perspective:** If we succeed, how will we look to our stakeholders?
- **Customer Perspective:** To achieve our vision, how must we look to our customers?
- **Internal Perspective:** To satisfy our customers, what management process must we excel at?
- **Organizational Learning:** To achieve our vision, how must our organization learn and improve?

Each perspective should be understandable, interpreted uniformly across the organization, and provide an agreed-upon basis for decisions. Measurement should demonstrate organizational effectiveness in addressing each perspective. For instance, measurement parameters such as energy consumption, cost, reliability, and power quality should be determined from the organization's strategy and priorities in the way it meets customers' needs.

Moreover, the organization's rewards and recognition structure must be aligned to recognize those individuals responsible for improving any of the critical measures mentioned above. Measurements need to provide information across time to show trends, not merely present snapshots. Finally, most importantly, measurement should encourage collaboration in order to facilitate acceptance and buy-in across the organization.

The Role of Good Metrics in Benchmarking

Benchmarking is a systematic process of continuously measuring performance and comparing it against industry leaders or world class organizations. It is an action-based approach for gaining information to enhance performance. Benchmarking will improve the efficiency and effectiveness of an organization,

leading toward the reduction of overall costs and increased competitiveness.

Benefits of a Good Measurement System

A good measurement system helps an organization identify the needs of external and internal customers. It reveals not only the obvious but also the subtle elements of necessary core processes. Since a good measurement system reveals problems that can lead to bias, it serves as the first step toward fact-based decision making. The actual improvement from and impact of prior decisions can be presented in such a way that facilitates good decision making. Finally, as a self-assessment and improvement tool, a good measurement system identifies sources of problems, performance trends, process efficiencies and effectiveness, and opportunities for improvements.

Metering Priorities

The procurement and installation of a metering system is not a trivial decision. A significant amount of expenditure is required. Therefore, careful planning is essential. The first step is to determine what level of metering is desired; in other words, do we need to meter only the consumption of the entire facility or is there a need for submetering? Deciding between these two basic alternatives has major cost implications. In addition, if there is a need for submetering, deciding whether to meter building clusters, individual buildings, or subdivisions within buildings will also affect the project cost. Let us examine these scenarios briefly.

The main meter that measures and records the total consumption of a facility is the most important unit. This meter must be of "revenue grade," which implies a higher level of accuracy than other units. The degree and extent of submetering will be a function of the number of tenants and how energy costs for space is recovered. For instance, if the tenants, their operations, and hours of operations vary greatly, individual meters are preferred. In this case, every unit or tenant is charged directly for the energy consumed. On the other hand, if the types of operations among facility occupants are similar, the energy cost may be distributed based on square footage occupied by each unit or tenant, or some other variable such as hours of operations.

Chapter four discusses the appropriate technologies for revenue metering and submetering in more detail.

Measurement Process

Measurement process is the act of comparing an unknown quantity against a predefined standard. This implies that every measurement is an approximation. Normally, a measurement will contain both a magnitude and a unit (e.g., 3 kWh). A measurement can be direct or indirect. Simple measurements are done directly, like weighing an object to determine pounds or kilograms. More complicated parameters, such as energy, are measured indirectly. The *accuracy* of a measurement relates to how close the measured value is to the "true" value. The *precision* of a measurement relates to how often a measure can consistently be reproduced. In other words, if the dispersion among repeated measures is small, measurement precision is high regardless of how close the readings are to the actual value.

There is no single best process for developing a measurement system. However, it is important to measure outputs and outcomes rather than processes. To illustrate this point, assume one is interested in measuring the reliability of an electrical system. It is commonly agreed that preventive maintenance will improve system reliability. Collecting the number of hours of preventive maintenance measures the process. Collecting the number and duration of failures for a particular period measures the outcome. In measuring reliability, the outcome is the most relevant measure. Measuring the process can only prove useful if one is trying to find the correlation between preventive maintenance and reliability.

A general framework for developing a means to measure outcomes should include the following major steps:

1. **Identify Tasks.** Identify what is important to be measured. This can be determined by looking at the mission of the organization, identifying who customers are, and assessing what they value.
2. **Establish Goals and Metrics.** Determine the core activities and the critical tasks that are important to customers to ensure their satisfaction. This may include defining the metrics, standards, and goals that need to be met. Goals

should be attainable, economical, and consistent with organizational objectives. Translate these into data needs. It is important to define data elements clearly and to communicate them to everyone who will be involved in data collection, verification, analysis, and interpretation.

3. **Identify Responsible Parties.** Identify the individuals or entities that will need to collect the data. Determine the role of the organization, the utility, and third party if any other entity is involved. The identification of responsible parties will become more critical in the deregulated environment since the bilateral relationship that consumers have traditionally enjoyed is fundamentally changing and other parties such as third party generators and power pools are included.
4. **Data Collection.** Collect the data and devise ways to reduce, transfer, and store it. Make sure that the data collected is free of statistical and personal bias and is collected based on defined procedures.
5. **Data Verification.** Take adequate steps to verify the validity of data. This may involve reading data elements more than once, checking the data against default values, or examining if the data falls within the expected range.
6. **Data Analysis.** Analyze the data and transform it into usable information.
7. **Comparison.** Compare the data with goals or previously established benchmarks to identify opportunities for improvement.
8. **Implement Changes.** Evaluate whether you need to modify existing goals or establish new goals.
9. **Define New Goals.** Add new goals or modify existing goals for future data collection as the needs or priorities of the organization change.

chapter two

Introduction to Measurement and Utility Metering

Measurement is the process of comparing one or more quantitative characteristics of an object against a predefined standard. It is commonly expressed in magnitude and unit (e.g., 20 kWh). Both parameters are needed to determine a measure. For instance, if power consumption of a piece of electrical equipment is stated as 20, it is not useful unless the unit is also specified (e.g., watts, kilowatts, volt-amperes, kilovolt-amperes, megawatts, etc.). Similarly, if the unit is known without the magnitude, the information is insufficient to determine power consumption.

This chapter will define the basic units of measurement for both electric and nonelectric energy, define the common multipliers that describe the magnitude of a measurement, and discuss the basic utility rate structures and their impact on energy costs.

Electric Terminology

Electricity has transformed our lives in a far more fundamental way than all other forms of energy combined. Yet it is the least understood form of energy. Nonelectric forms of energy have a physical mass associated with them and one can easily sense the magnitude of their power. By contrast, the enormous energy of electricity cannot be felt directly. For facilities managers to better understand basic metering concepts, it is helpful to know some basic electric principles and common electric terminology.

Basic Electric Principles

Early electric systems were direct current (DC) systems. In a DC system the flow of current is unidirectional, similar to a battery. DC power systems are relatively simple to analyze and understand; however, they only play a minor role in electric distribution systems.

Today, the majority of electric distribution systems utilize alternating current (AC). In an AC system the electric potential and current oscillate like a sine wave. A complete oscillation wave is known as a cycle. In each full cycle, the current and electric potential change direction twice. AC electricity can be single phase or three phase.

Single-phase electricity is similar to a DC system. There is one path for the flow of electric current and it takes two wires to establish the path. An AC single-phase system is used for residential and small commercial and industrial loads. A three-phase system can be viewed as a combination of three AC power sources where their electric potentials and currents are 120 degrees different from each other. Because of the 120-degree phase angle, the return currents among the three phases cancel each other out. This means that instead of six conductor wires, only three conductors are needed to establish the three current paths. Three-phase systems have several advantages over single-phase systems:

- They require smaller wires to transmit the same amount of energy.
- Three-phase systems have better voltage regulation.
- Three-phase equipment has a higher energy density, so it is smaller than equivalent single-phase equipment.

However, AC power systems do pose a number of complications, although they are a small price to pay compared to the many advantages they offer over DC systems. One complication is associated with the concept of power factor.

In an AC system, the electric potential and current continuously vary similar to a sine wave. They can be in-phase or out-of-phase. In-phase means their waves move synchronously (both waves go through their peaks and valleys at the same time); out-of-phase means the electric potential wave is leading or lagging the current. The cosine of the angle between the current and electric potential is referred to as the system power factor. When the current and potentials are in-phase, the power factor is one (100%). When they are out-of-phase, the value is less than one (e.g., 90%).

If a power system only has resistive loads, such as incandes-

cent lamps or resistive heating, the electric potential and current will be in-phase. However, most power systems contain capacitors and inductors in addition to resistors. Inductance loads, such as motors and fluorescent ballasts, cause the electric current to lag the electric potential and that means the power factor is lagging and below unity. Low power factor causes several problems, including:

- higher distribution losses
- lower system capacity and efficiency
- possible utility penalty charges
- poor voltage regulation, which means the system will experience higher voltage variation when there is a load fluctuation

You can improve your power factor by adding capacitors to the system. The capacitor in effect cancels the impact of the system inductance, and if adequate capacitors are added, the power factor can increase to unity.

Units of Electric Measurements

For most physical parameters there is the need to qualify whether the unit of measurement is "English" or "Metric." With electricity, there is a standard set of units, which is basically metric. The most common electric units are as follows:

Volt—Volt is the unit that measures the electric potential between two points. Electric potential is analogous to pressure in a fluid system—it induces flow. Without electric potential there cannot be a flow of electric current. Volt is commonly indicated with a symbol "V."

Ampere—Ampere is designated with the symbol "A." It is a measure of the electric flow (current) in a conductor. An ampere of current is equivalent to a flow of one coulomb (6,280,000,000,000,000,000 electrons) per second. By convention, electric flow is assumed to move in the direction opposite the flow of electrons.

Ohm—Ohm is the measure of resistance along the path of the electric flow. It is commonly designated with the Letter "R" or the Greek letter Ω (Omega). If there is one volt of electric potential in

the electric circuit and the current flow is one ampere, then the resistance of the circuit is equal to one ohm. This relationship is called Ohm's Law. The reciprocal of resistance is referred to as conductance, and the unit of measurement is "siemense" or "mho."

Volt-amperes—This is a measure of the apparent rate of energy delivered to an electric load and is equal to the system voltage multiplied by the current. It is designated as "VA." It is an important measure for electric systems because the rating of electrical equipment is measured in VA.

Watt—Watt is a measure of the rate of real energy delivered to an electric load. Watts are volt-amperes multiplied by the system power factor, so the real power delivered to an electric load will always be lower than or equal to the apparent power. It is designated as "W."

Watt-hour—Watt-hour is the measure of the energy consumed by an electric load. It is designated as "Wh" and is equal to the system power multiplied by the number of hours it was delivered.

Volt-ampere reactive—This is a measure of the system's reactive power and is designated as "VAR." This unit is used in sizing capacitors for power factor correction.

Hertz—As mentioned earlier, the voltage and current of AC power systems are periodic—they cycle. The number of cycles per second is called frequency and the unit of measurement is Hertz (Hz). The standard power frequency in the United States is 60 Hz.

Fluid Terminology

All nonelectric forms of energy are associated with mass, volume, and temperature. The nonelectrical energy units that facilities managers commonly deal with are associated with heating and cooling systems. The primary unit of measurement for these systems is the British thermal unit (Btu) which is the amount of heat that raises the temperature of one pound of water by one degree Fahrenheit. Therefore, when measuring the amount of

energy delivered by a hot-water or a cold-water system, we need to know the flow rate and the temperature differential.

Cooling systems are commonly measured in tons. A ton of cooling is equal to the energy needed to melt one ton of ice in 24 hours, which is equivalent to 12,000 Btu per hour. Steam is commonly measured in pounds of steam or in Btu. It takes 977 Btu to convert one pound of water at 212°F to steam at 212°F. So one pound of steam roughly contains 1,000 Btu of thermal energy. When measuring steam for heating purposes, one need only measure the number of pounds of steam delivered since the amount of energy contained in a pound of steam is fixed. Steam quality is a measure of how dry the steam is. Steam at 212°F is referred to as saturated steam and is commonly used for heating. If additional heat is added to steam, the temperature will continue to rise and it becomes "superheated steam," which is used for industrial processing.

Finally, boiler horsepower (BHP) is a unit of heating that is commonly used in sizing boilers. A boiler horsepower is the amount of heat needed to convert 34.5 pounds of water at 212°F to steam, or 33,475 Btu.

Metering Scale

Units of measurement vary significantly in magnitude. So, in many cases it is important to use a multiplier to properly scale a particular parameter. The common multipliers are the set of prefixes listed below:

Kilo	one thousand times
Mega	one million times
Giga	one billion times
Milli	one thousandth of a unit
Micro	one millionth of a unit
Nano	one billionth of a unit

Utility Rate Structures

Utility rate structures vary widely for different energy sources. The utility rates for steam, chilled water, and gas are relatively simple. Electric rate structures are the most complex. Moreover, every utility company has a number of different rates and tariffs, and as they move into the deregulated environment, their rate

structures will become even more complex. Every facilities manager needs to be knowledgeable about the various tariffs offered by their local utility.

Electric Rates

The average cost of electricity in the United States ranges from about 4 cents to 12 cents per kilowatt-hour depending on geographic region and the particular rate structure. However, the total electric bill is derived from a number of different parameters. The major elements of an electric bill are as follows:

Energy cost—Energy cost is a function of the kilowatt-hours of energy consumed for a particular period multiplied by the unit cost of electricity per kilowatt-hour. Depending on the particular tariff the unit cost may be fixed or variable. In some tariffs there may be a higher "on-peak" rate for certain hours of the day and a lower "off-peak" rate for other periods. If the facility is charged based on a time-of-day rate structure, the energy rate may vary continuously. Some rate structures contain a sliding scale where the unit cost of energy is related to the amount of energy consumed.

Demand Charge—Demand charge is related to the maximum amount of power needed ("demanded") by a facility. The utility company measures the power consumption of large customers based on either a fixed or variable time interval, which is commonly referred to as the demand interval. The demand interval is typically 5, 15, or 30 minutes in length. A fixed interval refers to specific time intervals. For instance, with a 15-minute fixed window, the individual intervals may start on the hour, 15 minutes past the hour, etc. With a sliding interval, the largest power demand during any 5-, 15-, or 30-minute period is considered for billing purposes. Demand is measured in kilowatts or kilovolt-amperes.

Many utility tariffs contain a "ratchet" clause for demand charges. This means the peak power consumed by a facility during any demand window becomes the basis for demand charges for the entire year. The reason for the "ratchet" charge is that the utility must make the investment to have the capability to deliver the peak power demand at all times during the year. For most customers, the peak power demanded is set during the

summer months between 10 a.m. and 4 p.m. because of air-conditioning load.

Demand charges are a significant portion of the utility bill for most commercial and institutional facilities. It is very important to have a good control over the demand level and to devise safeguards against unnecessary increases in demand.

Load Factor—This is a parameter that measures the relative demand level of a facility in comparison to energy consumption. Load factor is the ratio of the kilowatt-hours of energy consumed divided by the peak demand times the number of hours during the billing period (LF = kWh/[kW × Total hours]). For a utility company, an ideal load is unity (i.e., the power consumption of a facility is constant). When the load factor is low, the demand charges may be a large portion of the total cost. Thus the total cost of electricity per kWh will be high.

Power Factor Charge—If the power factor of a customer is lower than a preset number, typically below 85 or 90 percent, the utility will assess a power factor penalty. The reason for the charge is that a low power factor increases transmission losses and reduces transmission capacity for the utility. The power factor penalty charge is to encourage customers to install the appropriate number and size of capacitors to raise the power factor to or above the preset value.

Fuel Adjustment Charge—If the price for primary fuels used to produce electricity (e.g., gas, oil, or coal) increases significantly faster than had been factored into the rates, the utility will pass along the cost increase to customers as a fuel adjustment charge. A fuel adjustment clause is commonly exercised during a volatile energy market.

Service Voltage Charge—This is a fixed charge independent of energy consumption. It is directly related to the voltage and size of service to a facility. The charge is usually a small percentage of the total bill.

Energy Rates for Nonelectric Utilities

Some campuses generate steam and chilled water centrally and may charge individual facility occupants for their consumption. In other cases, a campus may be purchasing steam or chilled

water from a neighboring facility. Therefore, it is appropriate to briefly discuss how the unit cost is calculated for these utilities.

Chilled water and steam usually have a simple rate structure—cost equals consumption times unit cost. For chilled water, consumption is in tons of cooling. For steam, consumption is in million Btu or pounds of steam. In some instances, there may be a different unit cost between summer and winter or the unit cost may vary on a monthly basis. The unit cost is determined based on variable costs such as the cost of fuel, chemicals, electricity, and water and fixed costs such as labor, maintenance, and depreciation. Since the fuel cost varies seasonally, it impacts the total cost.

However, in most cases the distribution of the fixed cost over the year may cause wider unit cost variation. For instance, since chilled water consumption is very low in the winter, if fixed costs are distributed equally for every month, a ton of cooling in the winter will be much more expensive than in the summer. Naturally, the reverse will be the case for steam. In other words, the steam costs in the summer will be much higher than the winter. One way to reduce the unit cost variation between the summer and winter is to vary the allocation of the fixed costs based on monthly generation of steam or chilled water. This means a higher percentage of the fixed costs will be allocated to the winter months for steam and to the summer months for chilled water.

Prior to deregulation, the rate structure of natural gas was very simple. Customers were charged for the cubic feet of gas supplied multiplied by a unit rate. In addition, there was a fixed service charge or connection fee. This was usually a small percentage of the total bill and was a function of the nominal pressure gas size of service. Today, a gas bill may include other components: a charge for the percentage of gas that was part of curtailable or noncurtailable rates (curtailable rates refer to services that can be interrupted by the utility and vice versa); a distribution charge if the gas was bought at the well head from a third party supplier; and a storage charge if one has bought some gas that is stored off-site.

chapter three

Metering Fundamentals

This chapter looks at some of the fundamental elements and components of utility metering—how alternating current is measured, common types of analog metering, present-day digital technology, and performance metering. This chapter also describes nonelectric meters and discusses the basic aspects of power quality.

Analog Metering

Although almost all new meters installed today are digital meters, there are still a large number of analog meters in use. A workhorse of the industry, analog meters have served us well for the past hundred years.

Before looking at the common types of analog meters, it is useful to understand how alternating current is measured. Analog meters and electric motors share similar operating principles.

Measuring Alternating Current

Measuring various electrical parameters in a direct current (DC) power system is straightforward since the voltage and current do not normally fluctuate. However, with an alternating current (AC) system, the voltage and current continuously fluctuate following a sine wave with an average value of zero. In this case, the AC voltage and current are defined based on the average of equivalent DC power, which is referred to as the root mean square (rms) value. This translates to the peak value of a clean sinusoidal voltage or current wave multiplied by 0.707. Therefore, the voltage or current value for AC power usually indicates the rms value since the average value of the full cycle AC voltage or current is zero.

Types of Analog Meters

Analog meters are primarily electromagnetic devices. An electromagnetic meter is based on Faraday's Law, which implies that an electrical potential is induced if a conductor crosses a magnetic

field. The electrical potential is directly proportional to strength of the magnetic field, the number of conductors, the angle that the magnetic field is crossed, and the speed of the conductor. Since all but the speed of the turbine is held constant, the voltage induced is directly proportional to the velocity of the fluid. These meters consist of a flow tube that senses the velocity of the fluid and the associated electronics to take the voltage that is generated and convert it into flow rate and amount of flow by integrating the flow rate over time.

The first electric meter was designed in the late 1800s. It was a single-phase electromechanical kilowatt-hour meter that weighed around 40 pounds and cost $40. Today, the modern version of such an electromechanical meter weighs less than 5 pounds and costs roughly $30. Typically these meters have an accuracy of plus or minus 2 percent, an average useful life of 40 years, and a failure rate of less than 1 percent under a wide range of ambient conditions.

D'Arsenval Meter. The most common type of analog meter is the D'Arsenval moving coil meter. It consists of a cylindrical iron core coil that rotates within a pair of magnetic poles (Figure 3.1). A needle extends from the center of the core; a spring works as a counter torque. When current flows through the coil, the needle

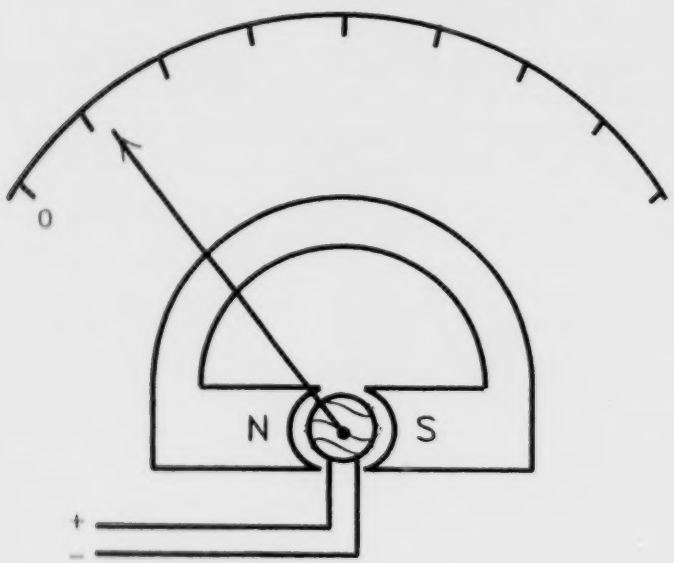

Figure 3.1 Schematics of a D'Arsenval Galvanometer

deflects clockwise or counterclockwise depending on the current polarity. The needle deflection is directly related to the current. The D'Arsenval meter is basically a galvanometer, which is the building block for most analog meters, including ammeters, voltmeters, and ohmmeters (Figure 3.2).

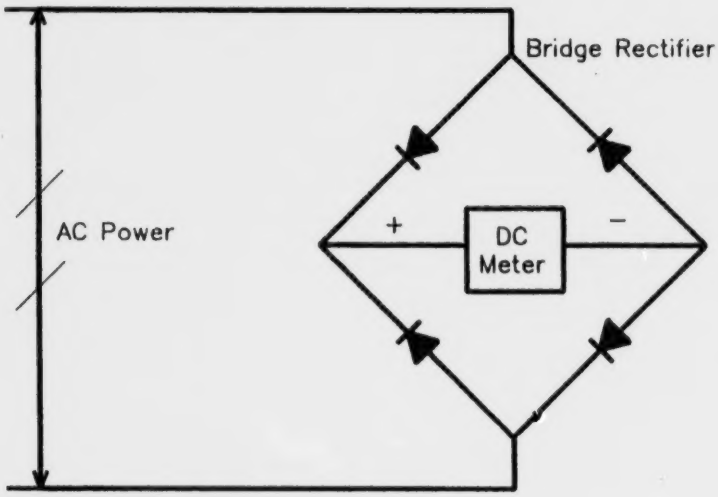

Figure 3.2 Schematics of an AC Meter

Ammeter. In order to transform a galvanometer into a DC ammeter, the current flowing through the meter coil must be limited. This is accomplished by installing a shunt strip across the coil (Figure 3.3). This divides the system current between the meter coil and the shunt strip where the two currents will be inversely proportional to the resistance of the two. This means only a small percentage of the total current runs through the meter while the bulk of the current is bypassed through the shunt. Adding several shunt strips and a selector switch accommodates different current levels.

Voltmeter. Similarly, a galvanometer can be converted to a DC voltmeter by adding a resistor in series with the meter coil (Figure 3.4). The value of the resistor will be a function of the line voltage and the meter resistance. Using a number of resistors and a selector switch accommodates multiple ranges. Both DC ammeters and DC voltmeters can be converted to AC meters by adding a diode bridge between the meter and the power source so the direction of current through the meter stays the same.

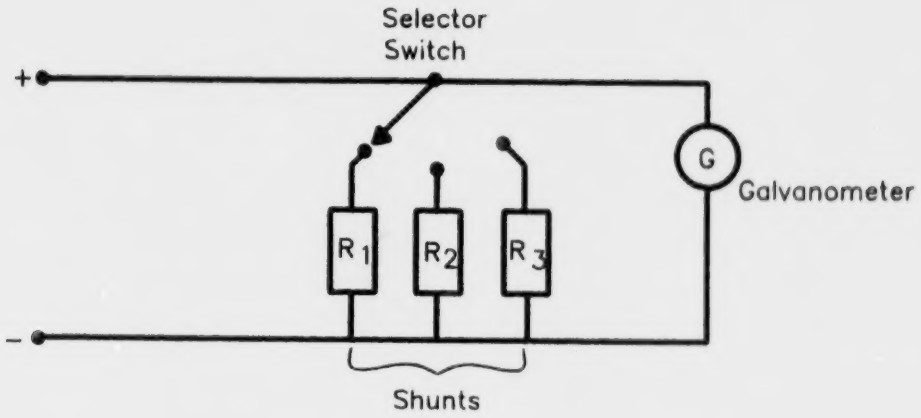

Figure 3.3 Schematics of a DC Ammeter

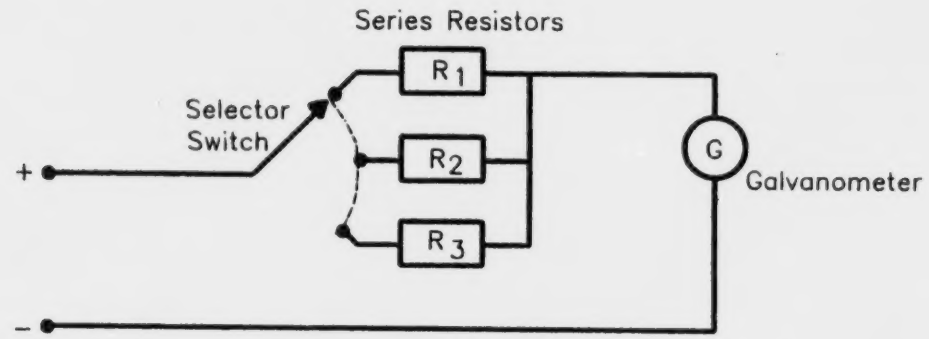

Figure 3.4 Schematics of a DC Voltmeter

Ohmmeter. To obtain an ohmmeter in addition to a galvanometer, a battery, a resistor bank, and a selector switch are needed. It is important to note that the scale of an ohmmeter runs in the opposite direction of the ammeter and voltmeter scale. This is due to the inverse relationship between resistance and current—the higher the value of the current, the lower the coil resistance and vice versa.

Dynamometer. A dynamometer is similar to a D'Arsenval meter; however, it contains two field coils and no permanent magnet. The needle deflection is proportional to the current and the number of turns of both coils. Although voltmeters and ammeters can both be dynamometer instruments, they are commonly

used for power measurements. Here, the ampere-turns in one field are proportional to the system voltage and in the second field are proportional to the line current. This way the needle deflection of the meter will be proportional to both voltage and current.

Power Factor Meter. A power factor meter is a special use dynamometer containing two coils connected in a particular way. If the two coils are connected in series with a resistor and the second is coil is connected in series with an inductor, the two coil currents will be nearly in quadrature. If the system power factor is unity, the meter will have maximum torque and the needle will move to full deflection. If the power factor is totally reactive, then the torque generated will be zero and the needle will not move. For any intermediate power factor values, the needle deflection will remain between the two in proportion to the system power factor value.

Moving Iron Meters. In a D'Arsenval meter, the bidirectional torque requires a diode bridge when used for AC applications. Unlike a D'Arsenval meter, a moving iron meter is a unidirectional unit, which eliminates the need for a diode bridge when measuring AC parameters. A moving iron meter consists of a pair of thin parallel iron vanes enclosed in a cylindrical coil. One of the vanes is stationary and the other one can move up to 90 degrees. The meter needle is connected to the moving vane. When the coil is energized, it induces a magnetic field that generates like poles in both vanes. Since like poles repel, the moving vane will rotate, which causes the needle to move. The scales in these meters are nonlinear, especially at the low end of the scale.

Other Meters. Meters can indicate instantaneous values or cumulative value. The display can be shown by a needle against a calibrated background, a set of digits that are mechanically driven by a set of gears, or light emitting diode (LED) or liquid crystal diode (LCD) with the associated electronics. In some cases, instead of a needle, the meter can have a rotating disk with an angular velocity that is proportional to the power usage and a counter that records the disk rotation. These are the basic elements of a kilowatt-hour meter. Some meters may have a recorder where the magnitude of various parameters can be

printed on a display tape or electronically saved in some form of nonvolatile memory.

Nonelectric Meters. Most of the old nonelectric flow meters consisted of a turbine and a set of mechanical gears connected to a dial and needle to display the magnitude of the flow. The cumulative value was displayed by a set of digits. Currently, there are two types of conventional flow meters in use, transit flow meters and Doppler flow meters. Transit flow meters are used when the fluid is clean and bubble free, for example in hot water or cold water applications. These meters can measure the flow with a high degree of accuracy. Doppler flow meters are not as accurate as transit types, but they can be used in "dirty" flows where suspended particles and bubbles are present.

Both types of meters use either the paddle wheel technique or the electromagnetic technique to measure flow. With the paddle wheel technique, a paddle wheel inserted inside the pipe is rotated by the fluid flow, which generates a pulse frequency. The frequency of the pulse generated is directly proportional to the rate of flow. With the electromagnetic technique, the pulses are transmitted to the meter electronics that in turn calculate the flow rate and the total quantity of flow over time.

Potential and Current Transformers

Metering devices are primarily low-voltage instruments. If the system voltage is greater than 600 volts, metering devices are not directly connected to the line voltage. Instead, the system voltage is coupled to the meter using a potential transformer (PT). Similarly, when the system current is more than a few amperes, a current transformer (CT) is used to connect the meter with the power system (Figure 3.5).

Potential Transformers

A PT is a low-loss, high-quality, step-down transformer. The turns ratio is tightly controlled during manufacturing to insure a high degree of accuracy. The rating of the primary voltage is the same as the rated line voltage and the secondary voltage is 120 volts. The primary side of a PT is marked with H1 and H2 and the secondary side is marked as X1 and X2. There are two dots, one on the primary connection (line side) and the other on the secondary connections (load side). These dots determine the

Courtesy of Cutler-Hammer

Figure 3.5 Potential Transformers and Current Transformers

polarity of the PT. If the current in the primary circuit is flowing through the dot, the current for the secondary circuit will be coming out of the line with the dot.

For a three-phase circuit, two PTs are usually adequate. Although PTs are high-quality, low-loss devices, the loss is not zero. For most of a meter's range, the accuracy is better than 97 percent. The lower the secondary current, the lower the losses, and in turn the greater the reading accuracy.

Current Transformers

In most cases, it is impractical and costly to let the full system current flow through the metering devices. A current transformer (CT) is used to lower the system current to a small fraction of line current. A CT is a doughnut-shaped metal core winding placed around the conductors of each phase. The line conductor serves as the primary winding and the doughnut serves as the secondary winding. CTs are sized based on the primary and secondary ratios, such as 100:1 or 200:1, etc. When the primary current is at its rated value, the secondary current will be five amperes. This means if a CT is properly sized, the output current under normal circumstances will always be lower than five amperes.

Current transformers are constant-current devices, which means the secondary circuit must always be closed. If the circuit is opened when energized, extremely high voltages will be generated between the terminals of a CT that can result in equipment damage and personal injury. This is why, unlike PTs, CTs are never fused and shunting strips are used when working on instruments that contain CTs. The CT polarity is also an important factor to pay attention to. The primary current should go through the primary connection dot and come out of the dot on the secondary side.

Determining PT and CT polarity

The polarity of a PT and CT should be carefully checked during installation. Otherwise, there is a good possibility that the meter may give erroneous readings or move backward. Similarly, wrong polarity in relays can result in false tripping or improper operation. If the polarity of a PT or a CT is not known, the correct polarity can be easily determined using the following simple procedure.

When facing the primary winding of a PT, the right terminal is H1. Connect H1 to one of the secondary terminals, as shown in Figure 3.6. Place one voltmeter (Ea) between the primary terminals, and a second one between H2 and the remaining secondary terminal (Eb). Energize the primary voltage and compare Ea with Eb. If Eb is larger than Ea, then both fluxes are additive, which implies that H1 is connected to H2. If Ea is larger than Eb, it implies that the fluxes cancel each other out and H1 is connected to X1.

To determine the polarity of a CT, a battery with a switch and a DC ammeter is connected as shown in Figure 3.7. If the polarity of the CT is chosen properly, when the switch is closed the current will rise suddenly and drop to zero. A second technique is to install a CT with known polarity and turns ratio with the unknown CT. Then connect the two with an ammeter. If the polarity of the unknown CT was chosen correctly, the ammeter will read zero. This means the current from one CT will flow through the other and no current will flow through the ammeter. If the polarity of the unknown is reversed, the ammeter will read the sum of the currents in both CTs, which can be as high as 10 amperes.

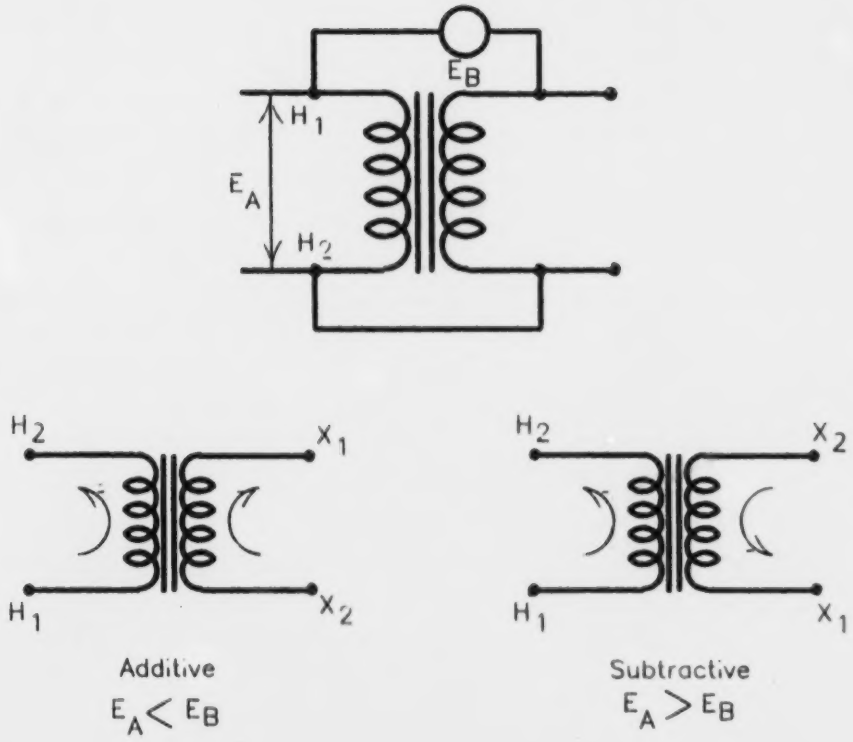

Figure 3.6 Polarity Test for a Potential Transformer

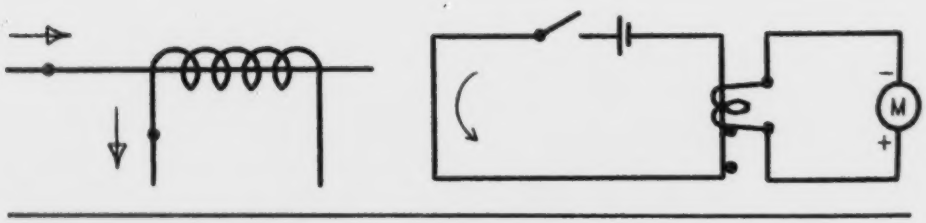

Figure 3.7 Polarity Test for a Current Transformer

Solid-State Metering

The first electronic meter was introduced in the late 1950s. The early versions were actually hybrid meters that contained both mechanical and electronic components. The first totally electronic meters were introduced in the 1970s. These meters were more complex, more expensive, less reliable, and more sensitive to ambient conditions than their electromechanical counter-

parts. Consequently, electronic meters were little used for many years.

However, three unrelated developments changed this slow proliferation. First, the advent of microprocessors opened new horizons of programmability for electronic meters not easily attainable with electromechanical units. Secondly, major technological breakthroughs tremendously improved the reliability of electronic equipment and reduced its cost. And finally, electromechanical meters cannot easily accommodate the recent development of more complex electric tariffs such as real-time and seasonal pricing. The use of electronic meters is a must as utilities move toward a deregulated environment.

Another issue of importance today is demand readout. Solid state meters can accommodate reading electric demand in a "sliding window" whereas electromechanical meters can only read demand in a "fixed window." Also, when demand readout is added, the failure rate for electromechanical meters is between 4 percent and 8 percent, which is more than double the rate for comparable solid-state meters.

Performance Metering

Deregulation of electricity has fundamentally changed the relationship between local utilities and their customers. The end user can now choose who to purchase power from. In an effort to retain customers local utilities have begun offering a variety of new value-added services including metering. In the regulated environment, metering is somewhat simple and straightforward. Metering is installed at the point where the utility's distribution system connects to the customer.

In the deregulated environment, metering is much more complicated since there are several exchange points between various entities before electricity is delivered to the end user. The first exchange point is between the generating company (GenCo) and transmission company (TransCo). The second point of transition is between the TransCo and local distribution company (DistCo). And finally, the last transition point is between the DistCo and the end user.

In some instances, there may also be independent power operators (IPOs), power pool councils (PPCs), and energy service companies (ESCOs) between the generation companies and the end users.

Since transmission losses exist between every transition, accurate and reliable performance metering is needed to track the losses and prevent billing disputes. Metering in the new environment should have the ability to

- verify suppliers' invoices and perform the required energy balances between various entities
- consolidate the bills for a number of different sites and service points into one bill
- support real-time pricing systems to facilitate decisions on consumption profiles and different suppliers
- accommodate interruptible rates
- address power quality issues such as harmonics, transients, and noise problems as well as monitor and record other abnormal distribution conditions

Until recently, panel-mounted metering devices for power switchgear were electromechanical. Since these units have moving parts, they are saddled with all the typical limitations of electromechanical technologies such as drift problems, low accuracy in the low end of the scale, and no capability for remote monitoring. Digital technology overcomes these limitations. Solid-state meters are more reliable, highly accurate over most of the measuring range, and the data from the meters can be monitored on a real-time basis and analyzed and processed remotely. These panel meters also have the ability to locally calculate, analyze, and store valuable information about the system. This feature is very useful for maintenance staff.

Metering for Nonelectric Utilities

An effective campus-wide plan requires consolidating utilities and automating metering data from all utility sources including steam, chilled water, and hot water, which sometimes employ nonelectric meters. To this end, it is important to have a basic idea about the operation of these meters.

The most common types of nonelectric meters are orifice plate, venturi, and turbine. The principle of operation for orifice plate and venturi meters is measuring the differential pressure across two points. Since the square root of the differential pressure is proportional to the rate of flow, the differential pressure is

calibrated to indicate the flow rate. The benefit of these two techniques of flow measurement is they do not require frequent calibration. However, proper sizing and correct installation is very important. The major drawback of an orifice meter is lack of accuracy if the load modulates over a wide range.

To calculate the thermal energy of steam, pressure and temperature must be measured as well as flow rate. However, since the temperature and pressure of saturated steam remain constant for any flow rate, additional sensors at each metering point to determine these parameters are unnecessary as long as the information is collected somewhere in the plant.

Data from the orifice plate or venturi meters can be converted to a 4–20mA signal and connected to a building automation system for remote monitoring. This offers access to instantaneous readings as well as total energy consumption rate.

Several metering technologies are used for measuring chilled water and hot water. The most common meters are orifice plate, annubar, venturi, and turbine. The first three types measure the differential pressure and convert it to flow rate using a calibration constant. Turbine type meters are rotating devices where the speed of rotation is proportional to the rate of flow. In addition to the flow rate, temperature sensors located at both the supply and the return lines help to determine total energy consumption. As mentioned above, these meters can be integrated with the electric metering network using a standard 4–20mA signal.

Power Quality

Traditionally, facilities administrators have only been concerned with electrical distribution parameters such as voltage, current, power factor, and frequency. However, with the increasing proliferation of nonlinear electrical devices, electrical distribution systems are becoming cluttered with harmonics, transients, and electrical noise. Today, plant managers must also be aware of these power quality problems and take the necessary measures to safeguard against them. Without safeguards, there is a good chance that a facility will be plagued with premature hardware failures, data corruption, and computer lockups. It is important that every facilities manager becomes familiar with the basic aspects of power quality, learns how to monitor them, and knows how to protect electric systems from low power quality condi-

tions. The first step in this process is to understand a number of common definitions:

Power Outage. This is when the voltage in the system drops below 80 percent of the nominal level for more than two seconds.

Undervoltage/Overvoltage. These conditions occur if the system voltage drops to 80 percent of the nominal voltage (undervoltage) or rises to 110 percent of the nominal voltage (overvoltage).

Sags/Swells. Undervoltage and overvoltage are referred to as sags and swells if the condition lasts for less than two seconds.

Percentage THD. Percentage of total harmonics disturbance (THD) is the square root of the sum of the square of the harmonics divided by the fundamental voltage.

Displacement Power Factor. This is the ratio of the fundamental frequency real power divided by the fundamental frequency apparent power.

Apparent Power Factor. This is the ratio of the total real power (including power from the fundamental voltage and current plus the harmonic voltage and current) divided by the total apparent power.

K-Factor. This derating factor is related to the sum of the square of the harmonic currents multiplied by the square of the harmonic number.

Crest Factor. The ratio of the rms current to peak current is defined as the crest factor.

CBEMA Factor. This is a transformer-derating factor defined as a pure sine wave's crest factor (Figure 3.8), which is 1.414, divided by the measured crest factor.

The majority of power quality problems stem from lack of good grounding. So, good grounding systems can mitigate most of them. The balance of power quality problems stem from harmonics and power disturbances.

Harmonics are due to nonlinear loads, such as variable frequency drives, fluorescent and arc discharge lighting, computer equipment, and noninterruptible power sources in the

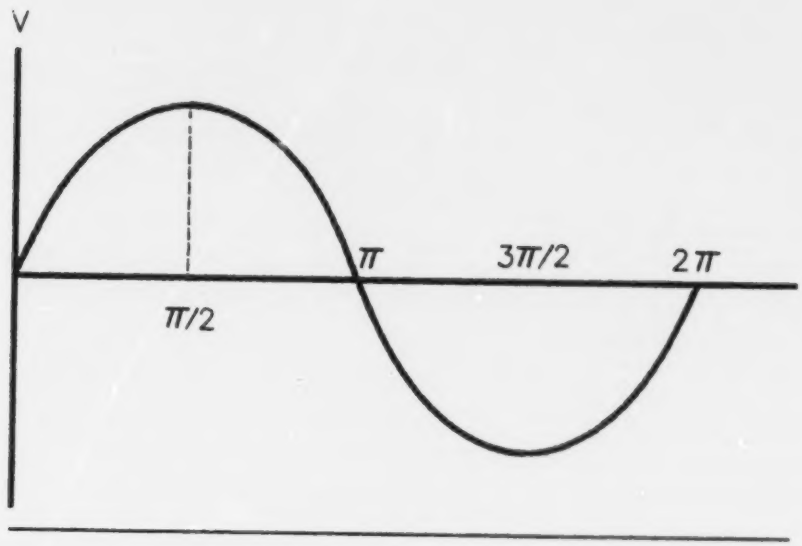

Figure 3.8 Sinusoidal AC Wave

distribution system. When such devices are operated, in addition to the 60Hz line frequency current, there will be a number of other smaller currents whose frequencies are multiples of the line frequency, namely 120Hz, 180Hz, 240Hz, etc. These currents are called harmonics (Figure 3.9). The relative values of individual harmonics are a function of the particular load. Although the magnitudes of these currents are much smaller than the fundamental current, their negative impact on the system can be severe. In practice, the harmonics that cause most problems are the third, fifth, seventh, eleventh, and the thirteenth. Some of the common problems associated with harmonics are:

- failure of electronic components
- lower system power factor that may result in power factor penalty charges
- erratic operation of relays and other monitoring devices
- faulty readings of electrical meters
- nuisance tripping of circuit breakers
- computer memory scramble and hard disk crashes

Power disturbances are random and sporadic power spikes that may only last a few microseconds. Power disturbances are either transients or noise. If the magnitude of the power spike is

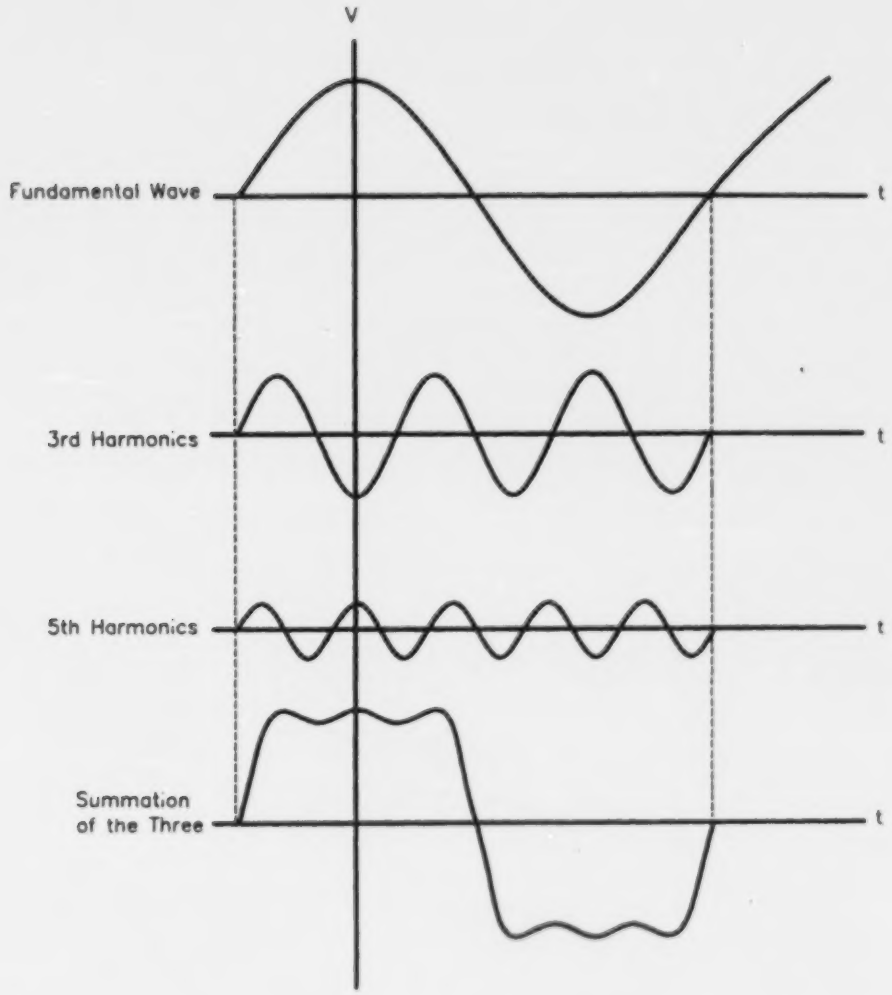

Figure 3.9 Wave Synthesis

twice the line voltage or higher and lasts between half a microsecond and 200 microseconds, it is called a transient. If the magnitude of the spike is less than twice the line voltage, it is called noise. Both transients and noise can result in such subtle and mysterious problems as failures of electronic equipment, data corruption, and computer memory loss. According to an Electric Power Research Institute (EPRI) report, power quality problems resulted in 37.3 million hours of lost productivity in 1991. The cost to U.S. businesses due to power quality problems is estimated at $400 billion annually.

Courtesy of Cutler-Hammer

Figure 3.10 Portable IQ Analyzer

chapter four

Metering Technologies and Products

The integration of microprocessor technology and other advances in energy metering have allowed the development of more complex rate structures. These new tariffs give utilities a means to influence customer load profiles and to reduce the overall cost of electricity. Similarly, these rates create opportunities for the informed customer to seek new and innovative ways to reduce its overall energy bill.

This chapter introduces a number of metering products that are currently available in the market. These products are not organized in any particular order and the inclusion of any product is not an endorsement by the author or by APPA, EPRI, or IFMA. The primary source of information concerning these products is the manufacturers' literature. The list of products included here is only a small sample of the range of products available today. This information is intended to give the reader a general idea of the capabilities of these devices as they analyze the needs and requirements of metering systems for their own facility. There is a plethora of new devices available from many manufacturers. The challenge is to pick a system that best meets your needs at a reasonable cost.

Nonintrusive Appliance Load Monitoring Systems

In the past several years, a new method of load monitoring has been introduced that allows useful energy data collection without intrusion. This technique is called Nonintrusive Appliance Load Monitoring System (NIALMS).

Electric Appliances

One type of NIALMS device can be installed in a regular kilowatt-hour meter. The device collects data and can transmit it to an energy management or billing computer system. In addition, a NIALMS device contains special pattern recognition software that can determine the energy consumption of particular appliances. Using data from NIALMS can give facilities mangers better

insights on run time for various loads and power consumption patterns. This information can help determine the loads that most impact the overall load profile.

Moreover, NIALMS can identify faulty appliances by sensing abnormal energy use and can possibly serve as an early warning system before actual failure. Similarly, in situations such as sump pumps where one expects a load to be intermittently operational, NIALMS may serve as a monitoring system to alert maintenance staff to potential trouble spots and avert possible floods.

This device was primarily developed for residential use. For a university campus NIALMS may be applied in residence halls, apartments, and other small or remote auxiliary facilities, especially when there is a need to determine the use patterns of individual large electrical appliances such as window air conditioners, washers, dryers, electric ranges, ovens, and water heaters.

Nonelectric Appliances

Installing conventional flow meters is normally an intrusive process—the flow has to be turned off and the plumbing changed. However, an ultrasonic device measures flow without penetrating the pipe wall. It does not require any service interruption, and since no barrier is introduced along the path of the fluid, no additional pressure drop is created. Because these solid-state units have no movable parts, they are inherently more reliable than traditional flow meters. Also, any maintenance and repairs can be done without any flow disruption. These meters have a disadvantage in that they are expensive in comparison to conventional flow meters such as paddle wheel type units.

NIALMS meters can also measure heating or cooling energy for HVAC systems with a high level of accuracy and reliability. Again, the main advantages of NIALMS meters over intrusive metering systems are ease of installation—no need to cut or drill the pipe—and uninterrupted operations. The system does not need to be shutdown during meter installation. The units can be portable or dedicated meters. Both types have the capability of communicating to an energy management system. Their calibration sensitivity and stability are much higher than for conventional intrusive meters, and units are available for a wide range of pipes: roughly from as small as ½" to as large as 48" in diameter and with wall thicknesses of 0.015" to 3".

NIALMS meters have several other advantages over intrusive meters:

- They operate from zero flow up to the rated flow of the pipe without any appreciable error. In contrast, some of the conventional intrusive meters such as vortex and turbine flow meters, are not very accurate at low flow conditions.
- No calibration deterioration occurs from sensor wear since the sensors do not come in contact with the fluid.
- No pressure drop results from the sensors because they are mounted on the outside surface of the pipe.

NIALMS meters consist of two pairs of clamp-on sensors. The first pair has two temperature sensors that are installed on the supply and return of the heating or cooling coil. They determine the temperature change across the coil. The second pair is installed on the return side and measures the flow. The signals from these four sensors are fed to a microprocessor that computes the energy delivered to the unit. The data can also be transmitted to a remote location using a standard communication protocol such as RS-232 digital data with data time stamp. This enables one to plot energy consumption over time. These meters also have other valuable features such as cavitation and aeration alarms and security code protection.

Electric Metering Networks

In the past several years, a number of manufacturers have introduced a series of power monitoring hardware and software solutions for electrical distribution systems. A number of these products relate to metering applications that are briefly discussed below. The hardware units of individual devices can be connected as a daisy-chained system using shielded twisted-pair wires. These networks can support up to five lines each 10,000 feet in length and can communicate with such other building automation systems as Wonderware, Johnson Controls, Honeywell, Allen-Bradley, Bailey, Expert Edge, Fisher-Provox, Siemens, Foxboro, Iconics, Intellution, and Modicon. The metering hardware devices can be loosely broken into four general categories: main electric meters, submeters, controllers, and analog interfaces for nonelectric parameters.

Main Electric Meters

Main electric meters provide highly accurate and reliable power monitoring data. They can be used as stand-alone units or in a network application. These units can measure over 70 electrical parameters including high-speed waveform recording and set-point monitoring. They can calculate thermal demand for all instantaneous and harmonic distortion values, sliding windows, and predicted demand for up to 10 parameters that are selected by the user in addition to setting minimum and maximum levels. Some units have a two-year calendar and can accommodate as many as 16 profiles per day per year. This allows definition of up to 10 tariffs with up to 8 rate changes per day in addition to 3 energy and 3 demand accumulators.

Some units can record minimum and maximum levels, events, and snapshot readings that can be time-stamped and stored in nonvolatile memory or can log daily, weekly, and monthly load profile graphs of demand, power factor, time-of-use, or billing calculations. They can accommodate up to several individual logs including one high-speed snapshot log. These meter units can have a logging capability from 2 cycles to 36 minutes at high speed. Snapshot logs can be independently triggered using standard set-point conditions. The units can store up to 100 time- and date-stamped records with a resolution as fine as one millisecond, and the logs can store up to 15 coincident values when a new extreme occurs.

These devices also show a number of important facts about the system in a built-in display that is easy to use. They are capable of power quality analysis, remote input monitoring, and control relaying, and have the ability for analog input and output communication. These units comply with the rigorous ANSI C12.16 Class 10 specifications used for revenue meters. Some units can measure the true root mean square (rms) reading up to the 50th harmonic and measure nonsinusoidal waves of up to 3.0 crest factor accurately. In addition, these devices can display magnitude and phase angles of even and odd harmonics, including the fundamental, and voltages and currents up to the 50th multiple.

Typical levels of accuracy obtained with these units maintained for wide reading scale range are:

- current and voltage ±0.2 %
- power, energy, demand, and frequency ±0.4 %
- power factor ±0.8%

The meters may have a dot matrix, gas plasma, or liquid crystal display (LCD) that can show several parameters simultaneously for real-time monitoring purposes. In some models, the display can graphically show the current and voltage wave shape in addition to the graphical harmonics of the Fourier spectrum. They can also display many other important power quality parameters such as percentage of total harmonic distortion (THD), K-factor, crest factor, CBEMA factor, magnitude, and phase angle of harmonics up to the 50th multiple. The unit can be triggered externally to capture a snapshot of this information for further analysis. And if the THD level exceeds a preprogrammed value, the unit can capture and relay the related information to another device.

In addition to harmonic analysis, some units can communicate power disturbance information. For instance, Waveform Display software can construct voltage and current waveforms, including the neutral and grounds, for up to 56 cycles. This information can be extremely valuable for identifying sags or swells problems for troubleshooting purposes. A reset threshold can be programmed to indicate the duration of the disturbance.

In addition to the features already covered, these units can also measure and display the following parameters:

- *Current:* the average three-phase current or individual phases, neutral, and ground current separately.
- *Voltage:* individual phase-to-phase, phase-to-neutral, and neutral-to-ground.
- *Power:* real, reactive, and apparent power for individual phases or the whole system.
- *Energy* (similar to power): real, reactive energy can be displayed for forward, reverse, and net quantities. This feature is very helpful if some in-house generation is connected to the system.

- *Frequency:* by time and date.
- *Demand:* real power (kW), reactive power (kVAR), and apparent power (kVA).
- *Power factor:* apparent and displacement power factor.

Moreover, a sizable number of mathematical and logic functions can be performed by some metering devices including

- arithmetic functions such as addition, subtraction, multiplication, and division
- comparisons such as greater/smaller, greater/smaller than or equal to, equality, and inequality
- logical functions such as AND, OR, TRUE, FALSE, NOT, and IF
- trigonometric functions such as SIN, COS, and TAN
- mathematical functions such as square root, power, sum, sum of squares, average, root mean square, log, natural log, minimum, and maximum

The communication system of these metering devices is generally compatible with RS-485 or RS-232 ports or both depending on the manufacturer and model. They can also support common industry communication standards such as Ethernet gateway (TCP/IP and OSI) or dedicated interface modules. The network hardware options include fiber optics, telephone system via modems, and radio communication where data rates of up to 19,200 bits per second can be accommodated. Many manufacturers offer Windows NT– and Windows 95–based software packages.

Submetering Devices

In large facilities, energy consumption data for the entire campus may be adequate for budgeting and accounting purposes but insufficient for energy management purposes. Moreover, in many campus buildings there are tenants that should be charged separately for their energy consumption. For these applications, one needs to install submeters. In principle, there is little difference between main electric meters and submeters, but these devices are not revenue grade meters and generally have fewer capabilities than main meters. However, they offer a cost-effective solution for such applications.

Submeters can measure watts, peak demand, and watt-hours within acceptable accuracy, and thus replace the need for individually mounted voltmeters, ammeters, frequency meters, and watt-hour meters. Therefore, the units save cost and space and provide communications capability for central data collection and monitoring. Also, many of these meters may have built-in current transformers (CTs), which improve the overall system accuracy since external CTs may add inaccuracies of more than one percent.

Submeters can be programmed to alarm at certain abnormal conditions, for instance, if the peak demand exceeds a predetermined maximum level or the devices become inactive. Some of the units can communicate data at 1,200 or 9,600 baud or both using shielded twisted-pair wire to a maximum distance of 7,500 feet. And some of the units can display present peak demand, peak demand with a time stamp, and programmable demand windows for 10-, 15-, 30-, and 60-minute windows. The demand window can be synchronized with the utility synch pulse so all demand windows start and stop at the same time.

Controllers

Controllers are load monitoring devices that work in tandem with metering equipment. These devices can provide alarm and control capabilities for an effective energy management system. Their capabilities include monitoring voltage, current, power, energy, power factor, harmonics, percentage of harmonic up to the 27th harmonic, and THD distortion.

Some microprocessor-based controller devices can control solenoid-switching breakers. These units are mounted in the conventional electrical panel board with identical power and branch wiring. The breakers can be turned on or off remotely. They can also be programmed to disconnect a load if the power demand reaches a predetermined value or if THD exceeds a certain threshold. In addition, these controllers can be programmed for up to 12 on- or off-hours per day for each breaker and can accommodate 20 holidays of up to 30 days duration each. Some devices have the capability for astronomical scheduling for over 300 preprogrammed cities as well as memory loss protection, power failure recovery, and brownout recovery.

Interface Module for Nonelectric Parameters

Interface modules are analog data acquisition devices that monitor the energy usage information of nonelectrical energy sources and interface with central metering devices. In other words, they allow data collection for a variety of parameters such as natural gas usage, steam usage, water usage, temperature, pressure, compressed air, and equipment run time to a centrally monitored computer and on a real-time basis.

These devices normally monitor any standard 0–20 mA or 4–20 mA signal from conventional transducers and perform the required computations such as counting run time and calculating energy use. The inputs can be configured to

- Scale the signal to an engineering unit in the nonvolatile random access memory of the unit. Instantaneous values can be displayed in addition to average values. The time values are calculated by two user-defined time periods.
- Count pulses from a number of different input devices. The result can be displayed based on "X" number of pulses per minute or any programmed time interval. Moreover, the pulses can be recorded, totaled, and scaled based on predefined parameters. The data can be rolled over and recorded in the nonvolatile memory.
- Determine the run time of equipment. This means the unit will report the on or off status of equipment as well as the total time of the off-to-on transitions. There may also be a reset mechanism for run time that is "password"-protected so only authorized individuals can exercise this option. In addition to total run time, this configuration can record and retrieve the time of the last off-to-on and last on-to-off transitions.
- Calculate thermal energy in Btus (British thermal units). Three inputs are needed: one to monitor the flow, one to measure inlet temperature, and one to measure outlet temperature. The Btu figures can be reported as forward, reverse, and net. This feature is helpful if energy flow is bidirectional. The Btu figure can be averaged over a predefined period.
- Accommodate alarms based on preprogrammed conditions. In this case, the two outputs are configured to close or open based on alarm conditions.

Metering Software

All manufacturers of metering systems have developed proprietary software that can interface with their hardware. These software packages can define power cost centers based on various parameters. The inputs to the programs come from a set of digital electronic meters placed throughout a facility. The software can accommodate and support an array of utility rate structures such as different rates for on- or off-peak periods, weekday versus weekend, seasonal, and holiday scheduling. Many of these software packages are Windows NT– or Windows 95–based systems and provide metering interrogation and data collection. They can analyze and consolidate data and display graphically or nongraphically. The data can be integrated for consolidated bills that could include real-time pricing, interruptible rates, etc.

The main benefits of these software packages are to

- Compare different rate structures and identify the one that will be most beneficial to the facility.
- Allocate utility costs, including related charges such as taxes and power factor penalty charges to various units in a more accurate and fair way as opposed to arbitrary cost allocation schemes such as cost per square foot, number of staff members, hours of operation, or size of budget. This is very helpful for chargeback purposes when several tenants are housed in the same facility. In a university campus, this capability is especially useful when auxiliaries and general funds departments are housed in the same building or when a portion of a building is used for sponsored research. Since the units are charged based on actual consumption, there is a stronger motivation for them to save energy than when charged on a cost allocation basis.
- Store historical data that will provide historical trends for consumption and cost. These load profiles can be correlated with other operational data such as the activity level, occupancy, and number of items produced.
- Enhance accuracy by synchronizing all meters to the utility synch pulse calculation of "coincidental" peak demand.
- Process the relevant data and create bills for internal customers, thus eliminating the need for data entry and associated keyboard errors.

- Generate bills with "revenue class" accuracy since the software has the capability of real-time polling of individual meters that are synchronizing to the utility synch pulse.
- Verify the bills received from the utility.

Stand-Alone Electric Meters

Today, stand-alone electric meters can be fully programmable. They can measure three-phase energy and demand in block intervals or rolling intervals. These meters have autoranging capabilities that allow use in 120-volt, 240-volt, 277-volt, and 480-volt services. Some manufacturers provide dedicated PC-based software to customize meter scanning for diagnostics. These devices have nonvolatile memory for program register and optical communication ports for transmitting data at speeds up to 9,600 baud. The time-of-use (TOU) version of these devices may support complex TOU schedules—programmable for 4 daily schedules, 8 seasons, 16 holidays, and 8 rate changes per rate per day, and provide both cumulative and continuous data. The rated accuracy of these units at normal ambient temperature can be within 0.2 percent for unity power factor and 0.5 percent at 50 percent power factor.

The multifunctional versions of these meters can measure energy and demand for large facilities. The accuracy of some models easily meets or exceeds IEC Standard 687 and ANSI C12.16. The major parameters monitored and displayed include real, reactive, and apparent energy and demand, current, instantaneous voltage, power factor, voltage, reactive volt-ampere, and watts. Types of demand registered may include peak, block or rolling, cumulative, continuous cumulative, and coincident. Some of these quantities are bidirectional, which is useful for facilities with cogeneration units. These meters can be password protected to stop unauthorized reset or reprogramming and may be equipped with an RS-232 optical communication port.

Technologies for Data Communication

There are a number of different technologies used to connect the metering devices with the communication systems. The most common ones include optical coupling, ultra narrow bandwidth, and standard telephone wires.

Optical Coupling Technology

Optical coupling technology may also be used to retrofit existing single-phase electromechanical watt-hour meters so energy consumption data can be communicated to a central location. These microprocessor-based systems can be installed under the front glass of existing electromechanical units. These modules allow meters to

- be read remotely,
- accommodate time-of-use metering,
- provide peak demand metering,
- perform load surveys, and
- provide real time power outage reporting.

The data from the meter can be collected via telephone system or any other communication infrastructure. Data can also be accumulated and transferred periodically to a billing system. This technology also offers the possibility of reading many different models of gas and water encoders. In this case, the metering module is hardwired to the encoders. Data can be collected at the desired frequency and electronically transferred to a database. For colleges and universities, optical coupling technology may be applicable for university apartments, remote facilities, and other single-phase auxiliary loads.

Ultra Narrow Bandwidth

A second communication method utilized for collecting data from various field meters is based on ultra narrow bandwidth (UNB) communication technology. This technology uses an extremely narrow bandwidth that is about 0.001 Hz, so only very small quantities of power, typically 0.0003 watts, are required to operate the device. The disadvantage of narrow bandwidth is low speed; it may take from 15 minutes to almost two days to transmit data. Therefore, it should only be used in applications where a slow response does not hurt operations. The meter reader can be installed in an existing electromechanical single- or three-phase watt-hour meter. The transmitter uses the power lines to transmit data from the meter. Every meter is assigned a different frequency and transmission is continuous.

A receiver collects the ASCII data from many meters and then communicates the data to a computer via telephone lines, cellular phone, or SCADA. Data transmitted may include kWh, KW demand, voltage and current readings, gas and water readings, power outage, and load profiling. The transmitter permanently stores the data in EEPROM memory, which is nonvolatile. Every receiver can monitor up to 480 meter readers. A receiver can store up to 4 weeks of data before transmitting it to a computer for analysis and billing purposes.

Modems and Telephone Lines

Another approach for data communication developed by at least one manufacturer uses an existing telephone line. The field modules can collect, store, and communicate metering data from almost all types of metering devices (e.g., electric, gas, and water). There is a lithium battery in the module that lasts for over 10 years and powers the meter interface circuitry. At the heart of the system is a microcontroller, which counts and stores meter input and contains the communication interface. Information can be reported to a host computer as frequently as once every 5, 15, or 60 minutes or as seldom as once every two months.

The pulses from the meter are fed to the microcontroller, which also maintains a real-time clock and calendar. At predetermined time intervals or dates, the unit initiates a telephone call to establish communication via modem to a host computer. Since the system shares existing telephone service, no dedicated telephone line is required. Data transmission typically takes less than 3 seconds and the microcontroller automatically hangs up afterwards.

Data transfer is nonintrusive. For instance, if the telephone is in use, the microcontroller hangs up, or if someone picks up the telephone during data transmission, the microcontroller will hang up before the person realizes the line is in use. The host can also call the unit for data download or to reset the real-time clock. Over 100,000 meter sites can be handled by one host computer. Transmission speed is normally at 1,200 baud. An optional high-speed serial port is available that can transmit at 9,600 baud, using an RS-232 direct connection. These metering communication systems have been installed in Europe, the Far East, Canada, and the United States.

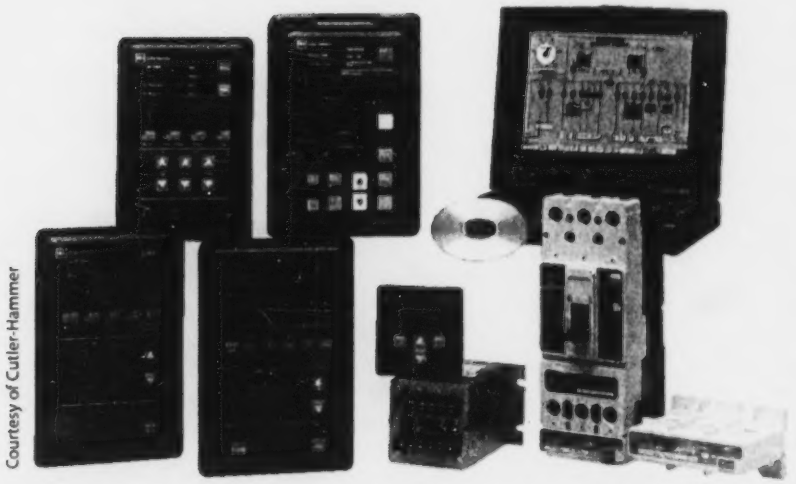

Figure 4.1 Power Management Measurement products family for electric metering networks

Figure 4.2 (IQ Analyzer) Typical Main Electric Meter

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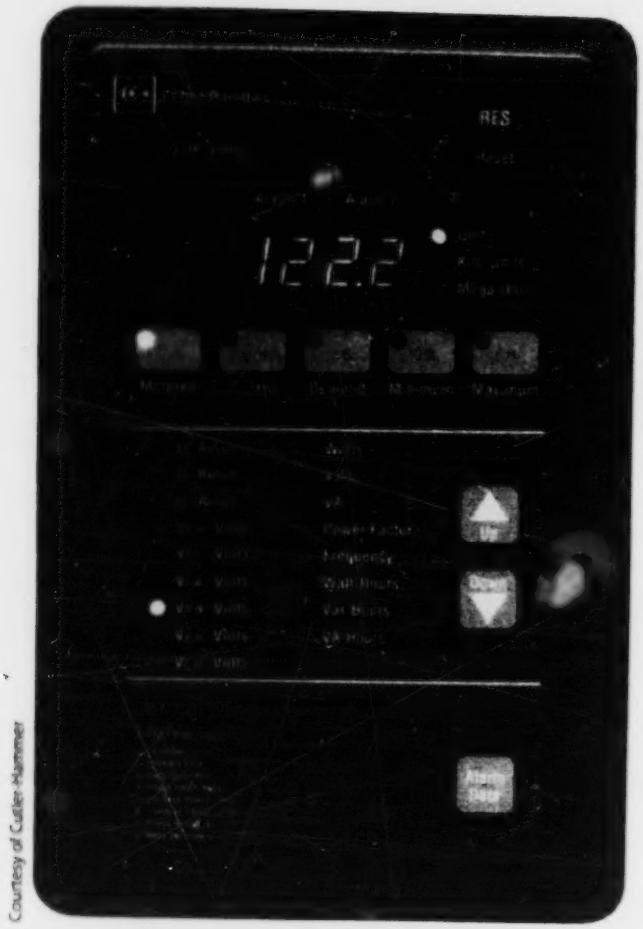

Figure 4.3 (IQ DP 4000) Typical submetering device for major load centers

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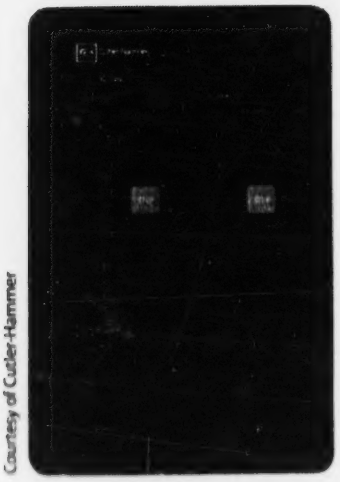

Figure 4.4 (IQ Data) Typical panel mounted meter; one meter replaces several analog units

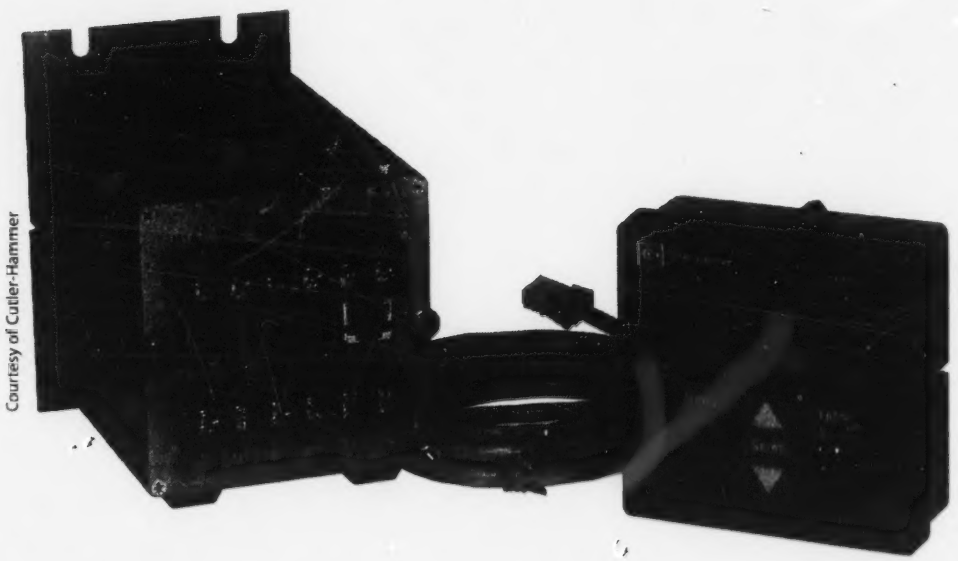

Figure 4.5 (IQ 200) Metering device that can be used as a stand-alone unit or part of a network

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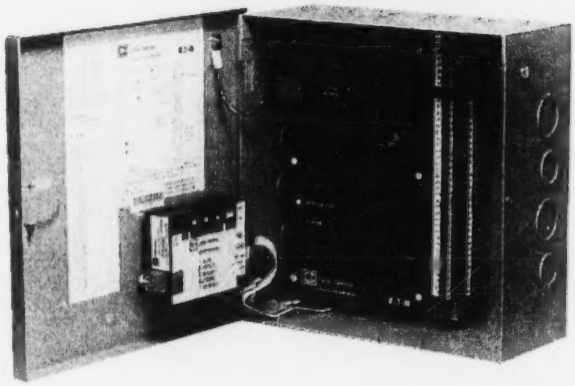
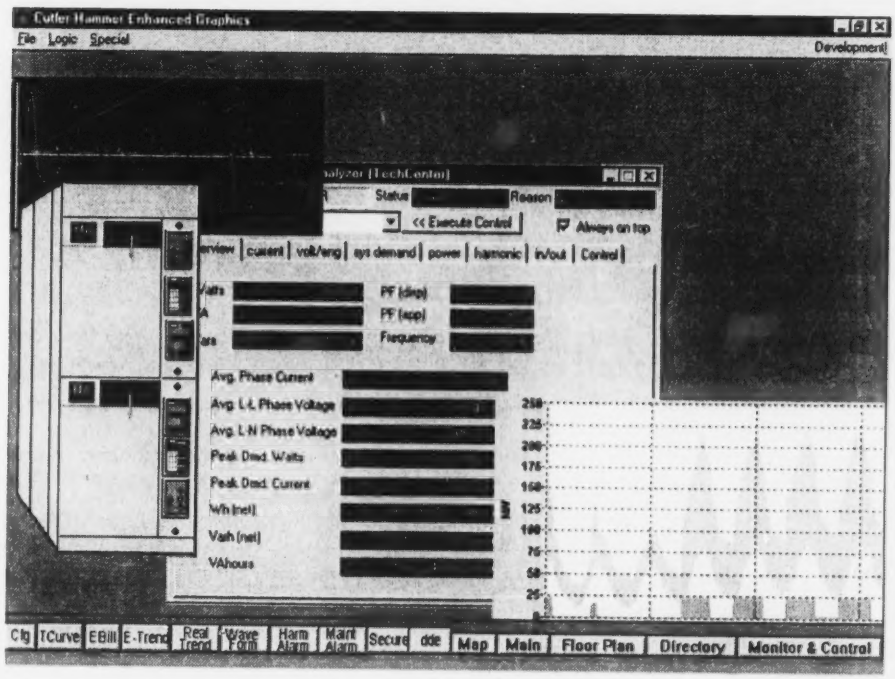


Courtesy of Cutler-Hammer

Figure 4.6 Typical Analog Input Module (AIM) used for interfacing nonelectric meters to electric metering networks



Courtesy of Cutler-Hammer

Figure 4.7 Power Net software display screen

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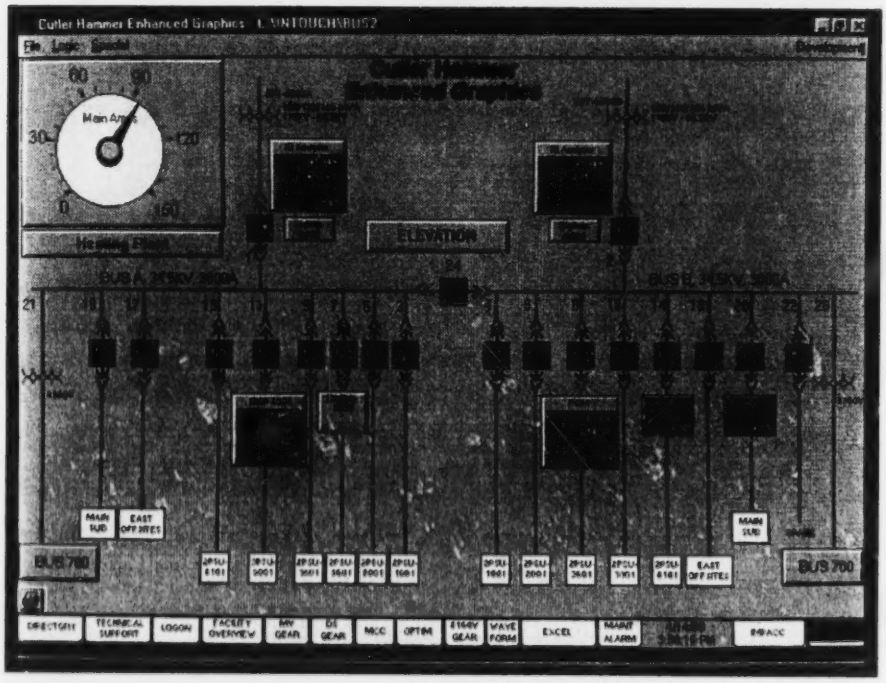
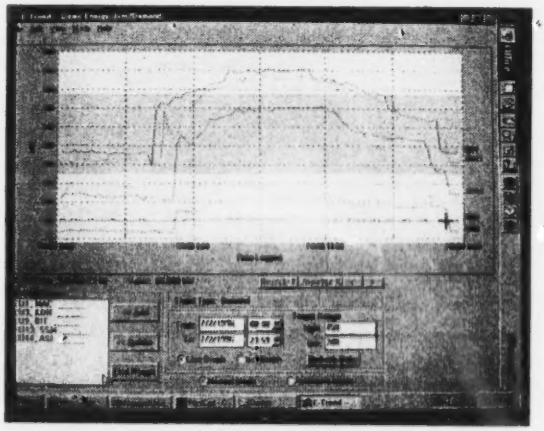


Courtesy of Cutler-Hammer

Figure 4.8 Network power software display screen



Courtesy of Cutler-Hammer

Figure 4.9 Network power consumption trend display

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chapter five

Management Aspects

There are roughly 3,600 higher education institutions in the United States with a combined annual operating budget of $165 billion per year. The annual maintenance and operations budget of these institutions is roughly $17.5 billion, of which $11 billion is spent on energy. Out of that $11 billion, roughly $6.5 billion is spent for purchased utilities.

For a typical campus, the operations and maintenance budget is roughly 8 to 12 percent of the total operating budget. Thirty-five to fifty percent of the operations and maintenance budget is spent on energy. Energy costs are a significant piece of an institution's annual budget.

The Role of Metering in a Deregulated Environment

The deregulation of electricity offers institutions a valuable opportunity to reduce their energy costs. However, if an organization does not pay close attention to the changes that lie ahead, its energy costs could increase at a much higher rate than at any other time in the past including the energy crisis of the 1970s. In the new deregulated environment the market forces are more complex than in the past. Reliance on anecdotal information on energy use is not sufficient to make astute choices. Accurate and timely energy use information is required.

The necessary infrastructure enabling an organization to make appropriate choices requires a system of integrated energy meters. These meters must be networked with associated software so that data from these units are converted to useful information. Real-time metering for data collection and analysis will become an integral part of the management decision support system.

It is essential that contracts for purchasing electricity from a third party quantify and explicitly state the facility's requirements. At a minimum, the specifications for electricity must stipulate steady-state incoming voltage, over- and under-voltage limits, total energy required, peak demand, power factor, and maximum total harmonic distortion, among other important

criteria that could be specified. To be sure that power supplied is within the specified limits, the facility must install adequate metering to monitor these parameters on a real-time basis.

Deregulation will impact power quality in a significant way. Although some managers worry that power quality may suffer, a larger contingent believes that energy suppliers will try to differentiate themselves in the marketplace by offering custom power—electricity with a predetermined quality level. In fact, "power branding" has already been tried in pilot applications. For instance, in 1994 the French National Power Company offered custom power with a predetermined quality level to 6,500 of its customers. In return, the customers were asked to install appropriate isolation devices to keep any electric noise or harmonic distortion generated in-house off the power grid. Similarly in the United States, some utilities are offering custom power to a select number of their large customers. Two examples of such contracts are the agreement between Detroit Edison and the three major automakers and between Ohio Edison and PPG. In each case, the utility guarantees to deliver electricity with a certain power quality level in return for a guaranteed power contract from the customer. These examples suggest that establishing a baseline of acceptable power quality will become a standard element of a power contract, which in turn means that power quality monitoring devices will become required elements at critical points in power distribution systems.

Strategies to Reduce Electric Energy Costs

One of the most important factors in negotiating the price of electricity, especially in a deregulated environment, is the shape of the load curve (or load profile). Ideally, the load curve should be flat, indicating constant power consumption during both peak and nonpeak periods. However, for most facilities power consumption varies and the load curve is similar to a bell shape. The role of a facilities manager is to seek opportunities to flatten the load curve and improve the overall load factor. One possible way to do this is to seek another facility, preferably one close by, whose load profile is a complement of your facility's load profile (i.e., where combining the two load curves produces a flatter profile.) Partnering with such a facility to purchase power is beneficial to both parties.

Interrelationship of Electrical and Thermal Energies

In addition to "partnering," there are a number of other steps one can take to improve the load factor by flattening the load profile. The key to several of these techniques lies in understanding the interrelationship between electrical and thermal energies.

Unlike electrical energy, thermal energy can be economically stored. This makes it possible to shift the load (flatten the load curve) by using stored thermal energy in place of electric energy at times of high power demand. The following two common techniques illustrate valuable opportunities for many facilities to make use of this relationship.

Precooling. Most buildings have sizable mass that retains heat and so prolongs conditioning for cooling or heating. If many buildings' cooling systems are brought on line at one time, the demand for cooling (or heating) increases tremendously, which, in turn, may increase the electric demand and result in significantly higher electric cost. One strategy to avoid this is precooling. If buildings are precooled by a few degrees before approaching the peak electric demand window, then the retained coolness in the building mass will reduce the cooling needs during the peak hours.

Thermal Energy Storage. During the past decade thermal energy storage (TES) has been increasingly used by many facilities to modify the electric load profile of a campus. The fundamental concept is very simple. Since electricity itself cannot be economically stored, TES is used to convert electricity to chilled water or ice during off-peak hours, and can also store heat. Subsequently, during peak hours when the price of electricity increases beyond a certain level, the electric chillers are throttled down or completely turned off, and the campus-cooling load is partially or totally met using the TES charge.

Other Cost Saving Strategies

Fuel Switching. There may be opportunities to switch the primary energy source for some services. For instance, some central cooling plants are equipped with a combination of electric chillers, steam-driven turbine chillers, and steam or gas absorption machines. This variety of cooling equipment allows the use

of different fuel source units based on the overall campus electric demand and the cost of producing chilled water by the different machines. For instance, the electric units may be base loaded (run at full capacity) during off-peak hours, then as electric demand goes above a predetermined level, chilled water production is shifted to steam-driven turbines and steam or gas absorption units.

Variable Speed Drives. There are many centrifugal electric loads such as pumps and fans that can be modulated by a variable speed drive without any appreciable impact on the building occupants. Since the relationship between air flow and energy consumption is cubic, even a small drop in the flow can result in an appreciable drop in power demand. For instance, a 10 percent drop in flow results in a more than 30 percent drop in power input to the motor.

Standby Generators. Many facilities have sizable emergency generators to provide back up power during an outage. Normally these units are utilized at most for only a few hours in a year and are idle the rest of the year. However, with the advent of real-time pricing (RTP) they can serve an additional purpose. The generators can be programmed to start up and connect to the system to reduce the need for utility-supplied power when the power demand or energy cost increases beyond a certain point. This strategy presumes that the generators are equipped with synchronizing gear so they can run in parallel with the incoming power. It's important to understand that the duty rating of prime mover and generator must be checked before implementing.

General Load Shedding. Many facilities have nonessential loads whose hours of operation could be changed to off-peak times without an appreciable impact on operations. With RTP, such load shifting and load scheduling can produce substantial dividends. Also, some other electrical loads could be cycled periodically to reduce overall energy consumption during peak hours. However, a "cycling" strategy should be examined to verify that energy savings would outweigh possible higher maintenance costs or system wear and tear.

Deciding What Needs to be Metered

In the first chapter, we discussed some of the general questions that need to be answered in developing any measurement system. The same set of issues is relevant to metering. These issues can be broken down into three major categories, on-site generation, energy management plan, and utility rate structure.

On-site Generation

On-site generation relates to any facility that has a cogeneration plant, standby generators, or a peak shaving program. The impact of each or any combinations of these is the same from the utility's point of view—they can reduce peak demand.

Cogeneration. If the cogeneration unit's capacity is larger than the minimum power demand, a portion of the power generated will be exported. In this case the facility needs adequate metering to monitor and record power flow in both directions. If imported power is required, the cogeneration unit will require adequate metering to calculate the cost of electricity on a real-time basis and to modulate generation based on the cost differential between in-house generation and imported power. When the cost of purchasing a unit of electricity from the grid is more expensive than in-house generation, the unit should run at full capacity. As the cost to purchase power drops below the in-house cost, generation should be reduced to the minimum level needed to meet the facility's thermal requirements.

Standby Generator. With standby generators, two-way power is not required, but metering and monitoring devices should be adequate to predict the oncoming peak demand of the facility and to monitor the total cost of generating electricity by the standby unit versus purchasing power from the electricity grid. When it is less expensive to purchase electricity, the standby generator can be shut down and vice versa.

Peak Shaving Program. In this case, metering can identify how much load needs to be shed. Proper submetering is required to indicate the impact of shutting down particular equipment, and proper monitoring and controls are required to accomplish these tasks automatically.

Energy Management Plan

An energy management plan may include reducing the consumption and demand of individual load centers as well as modifying the overall load profile of an entire facility. When an energy management plan is started, it is important to have the requisite meters installed to monitor the effectiveness of the program. Continuous feedback will not only show if the program is meeting its objectives, but also reveal insights on how to refine the plan and minimize energy costs. Moreover, individual meters for large loads provide the data to determine their efficiency. When efficiency drops below a certain level, investigate the reasons and take appropriate action.

Utility Rate Structure

Utilities offer a plethora of different rate structures. Some of the common tariffs include time-of-day rates, interruptible rates, real-time pricing, and performance-based rates. The metering needs of a facility depend upon the particular rate structure.

For a time-of-day rate, the demand cost will differ by on-peak and off-peak times as well as by season. The metering requirements for time-of-day rates are modest compared to other tariffs. Demand and energy meters for the main supply and large load centers may be adequate.

If a facility is on an interruptible rate, adequate metering and automatic control equipment is needed so the system can shed load based on a preprogrammed schedule in the event of power curtailment.

Real-time pricing requires the most complex metering system, especially if there is some level of on-site generation. The metering system must be able to measure the energy and demand power of the site and main branch circuits on a real-time basis, and have the controls to maintain the preprogrammed load profile.

In addition to energy and demand level, performance-based rates may be predicated on other power quality and reliability thresholds for the power delivered. The utility may receive a higher rate for metering or exceeding these thresholds or be penalized for failing to meet them. Continuous monitoring is needed to ensure that a facility is receiving the agreed-upon quality and reliability of power. The power quality parameters

typically monitored include voltage, frequency, harmonics, maximum fault current, and power factor. The reliability parameters that need to be monitored may include the number of momentary interruptions per year (a power interruption of roughly between 30 cycles and two minutes) and interruption duration.

Meter Specifications and Installation

The first step in acquiring an effective metering system is to develop a comprehensive set of specifications that accurately reflect the needs of the organization. A good place to start this process is to review the latest literature and product brochures of many meter manufacturers to learn what capabilities are available in standard products. Then, based on the discussions earlier in this chapter, determine precisely what needs to be metered at the facility. The manufacturer's brochures usually contain suggested specifications. However, it is important to develop a performance specification that does not inadvertently limit the choice of suppliers.

Once the metering system is selected, adequate safeguards are needed to ensure proper installation of the metering devices. Following manufacturer's recommendations for installation can minimize future problems. Improper installation of any device will compromise its performance. APPA is developing model specifications for procuring metering and monitoring devices to help facilities managers with this process.

Maintenance and Calibration

No matter what type of metering is installed, adequate care and maintenance is a prerequisite for keeping the units functional. The new digital meters are very robust, and most of them do not have a drift problem. Analog meters, however, lose their calibration over time due to scale drift. Periodically, they need to be checked for accuracy. The manufacturer's standard can serve as a good guideline for the frequency and level of maintenance. Another factor that should determine calibration frequency of a meter is the amount energy the unit is metering. A meter on a branch circuit that consumes a higher level of energy compared to another branch circuit should be tested more frequently. Many organizations do not have staff qualified to perform the

needed service. This work can be outsourced to an operations and maintenance (O&M) firm. In some cases, the local utility or its subsidiary offers these services.

Summary

Today most campuses and building complexes have only limited procurement metering for purchased utilities such as natural gas, water, and electricity. They may have primary meters for steam, hot water, and chilled generation and possibly a number of meters to determine the consumption of auxiliary facilities. These meters are usually read manually once a month for billing purposes, and in many cases the data is used for budget requests. However, the metered data are not part of any management decision support system.

Most institutions do not have adequate metering to take advantages of the opportunities to significantly reduce energy costs in a more complex deregulated environment. Moreover, if organizations do not invest in adequate metering to prepare for deregulation, they may experience significant cost increases. Although funding prospects for metering projects vary significantly from one institution to another, overall such prospects are bleak. However, several strategies have proved successful. One such strategy, used by a number of institutions, is to combine campus-wide metering with utility or energy conservation projects. Another strategy is to work with ESCO's to fund such projects using energy savings as the incentive. A third approach is to work with local utilities. In some cases, a local utility will offer metering services to its large customers to ensure customer loyalty.

Deregulation is fundamentally changing the relationship between electric utilities and their customers. However, only generation has been deregulated, and no matter where power is purchased, it is still delivered through the distribution system of the local utility. This creates a different dynamic and presents opportunities for cooperation and partnership between the local utility and large customers. Because of the expertise utilities have in metering, this is one potential area for partnering.

Even states and municipalities not directly impacted by deregulation in the next few years will likely feel the effects of

deregulation from neighboring states. Over time, everyone will be affected. In order to maintain their customer base, many utilities are beginning to work with large customers in a variety of ways such as providing technical assistance, offering new tariffs advantageous to both parties, or guaranteeing a certain level of power quality. Despite the challenges facing facilities managers, there are a number of new opportunities. To take advantage of these opportunities requires metering. A "wait and see" attitude on metering could easily result in "wait and lose."

appendix I

Basic Statistics for Managers

Statistics play a very central and important role in understanding and interpreting measurement data. Unfortunately, despite their critical role, statistical concepts are poorly understood by most managers. The purpose of this appendix is not to make the reader an expert in the topic. However, it attempts to give an overview of the fundamental concepts of statistics. Understanding these concepts will give managers a better idea of what information a data set is clarifying and, more importantly, what it is not revealing. As William W. Watt stated, "Do not put your faith in what statistics say until you have carefully considered what they do not say."

The Need for Data Analysis

The role of statistics is to separate good data from erroneous data. This is accomplished by narrowing the region of doubt. Statistics deal exclusively with precision (how often a measured value is consistently reproduced), not with accuracy (how close the measured value is to the true value). The added precision of statistics assists in determining what is good data and in eliminating faulty results. Data collection is expensive, so it makes sense to ensure that the collected data are relevant to the problem. Consider the following guidelines when planning for data collection and analysis:

- Define what information is needed.
- Identify what needs to be measured to get the required results.
- Determine the frequency and locations for the measurement.
- Ensure you have adequate meters with the appropriate level of accuracy to collect the data.
- Decide how data is going to be collected. Will the data collection be automatic, manual, or a combination of the two?
- State how the data will be analyzed.
- Identify individuals who will interpret and report the results.

In many situations, the amount of available data is large and collecting it all may be cost prohibitive. Statistics can assist us in determining the best sample of data to collect, in analyzing that sample, and in making inferences about the population. Large amounts of collected data can be difficult for most individuals to analyze unless presented in an easily digested format. Here again, statistics give us a variety of tools for analysis.

Basic Statistical Definitions and Concepts

Basic definitions and concepts for understanding and using statistics are outlined below.

Range. The range of a data set is the highest figure minus the lowest figure.

Mode. The mode is the data point with the highest frequency of occurrence (Figure I.1).

Median. If a data set is arranged in an ascending or descending order, the data point that is located at the middle of the set is called the median.

Mean. The mean or average is the summation of all data points divided by the total number of data points. Mean can be looked at as the center of gravity of the individual values.

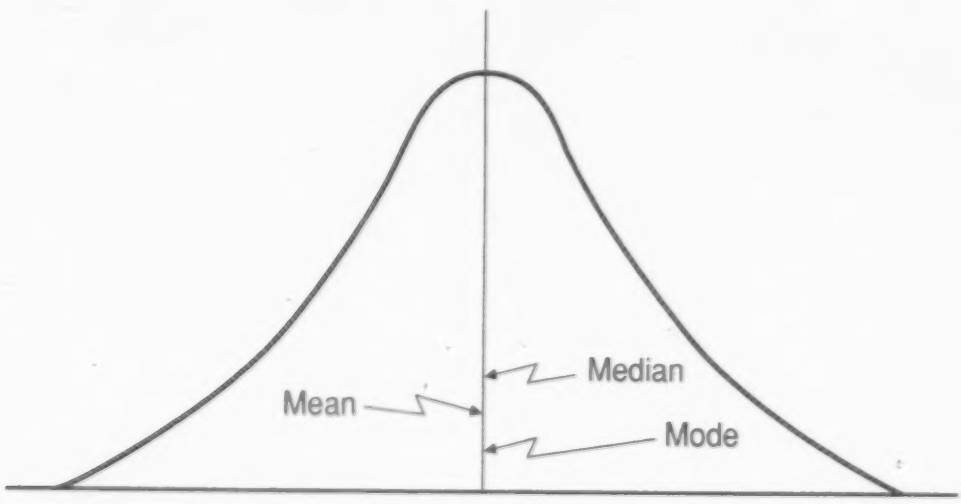

Figure I.1 Normal distribution

Variance. Variance is the average of the sum of the squares of the differences between individual data points and the mean. Variance is a measure of data dispersion. Low variance implies that data is tightly clustered around the mean and vice versa.

Standard deviation. Standard deviation is the square root of variance. In most applications one uses the standard deviation more frequently than variance.

Stochasticity. Stochasticity is a measure of how skewed a data set is (Figure I.2 and I.3).

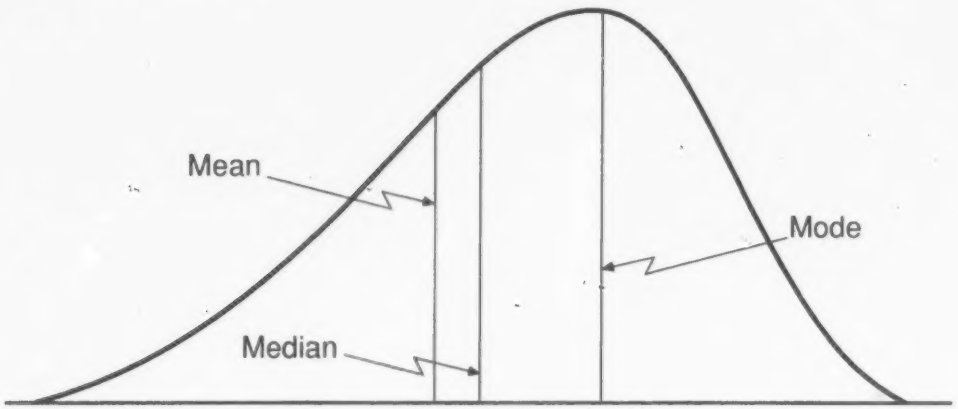

Figure I.2 Positively skewed

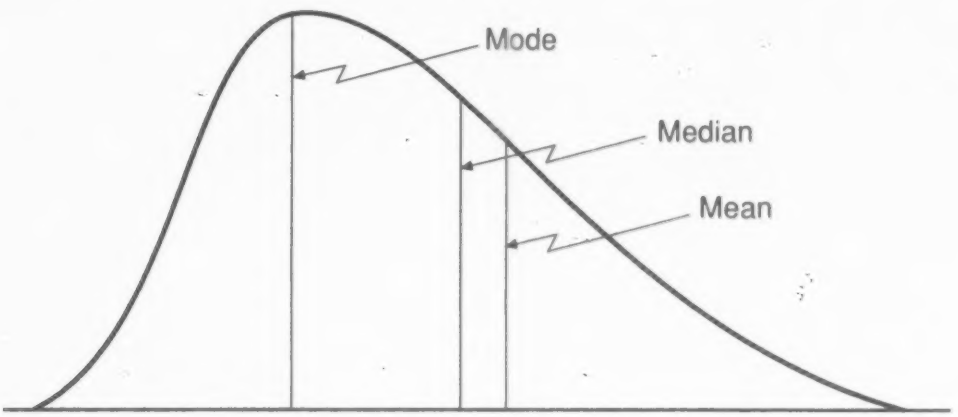

Figure I.3 Negatively skewed

Application of Statistical Concepts to Metering

There are three frequency distributions commonly encountered in data collection and analysis: binomial distribution, Poisson distribution, and normal distribution. Of these, normal distribution has the widest applicability, first because of ease of use and second because the other two distributions can be approximated fairly accurately.

Normal distribution is an idealized continuous distribution that has a nonzero value for any interval. That is why the curve never touches the horizontal axis (Figure I.4). This distribution is symmetrical about the mean and has a strong tendency. The mean, mode, and median of a normal distribution curve have the same value. Since the curve is symmetrical the stochasticity of the curve is zero—it is neither positively nor negatively skewed. The range of the normal distribution curve is from minus infinity to plus infinity. Data dispersion for a normal distribution curve can be determined easily. For instance, 68.26 percent of the data points are within one standard deviation from the mean, 95.46 percent of the data are within two standard deviations from the mean and 99.73 percent of the data are within three standard deviations from the mean. Using "T Distribution Tables" one can find the percentage of data from the mean for any other value. This property of normal distribution simplifies calculations tremendously. Illustrations of skewed distribution curves are shown in Figures I.2 and I.3.

When data has a normal-shaped curve, it implies that variations due to random and gross errors have been eliminated and variations due to systematic error remain. To analyze the impact of systematic error, the lower and upper tolerances for the variation can be drawn on the same sheet as the distribution curve. If the plus or minus three standard deviation limits lie within the tolerance levels, then there is no problem; otherwise, systematic error must be reduced.

Another important factor easily determined using normal distribution is process capability. This concept relates the dispersion of data to a desired level of measurement accuracy. This is important in assessing the ability of a metering system to accomplish its assigned task. Process capability is determined by plotting the data distribution curve and drawing both the upper and lower specification lines (USL & LSL) as well as the upper and

lower capability lines (UCL & LCL) of the particular measurement device. (See Figures I.4 to I.7) There are a number of possible scenarios.

- In the first case (Figure I.4), UCL and LCL are within the USL and LSL, implying that the process is capable, and the variation of data is well within the capability of the meter. However, this condition is not satisfied in the other three cases.
- In the second case (Figure I.5), the data average is centered about the mean, but the variation in measured data is higher than the upper specification limit for the meter.
- In the third case (Figure I.6), the data is centered about the mean but outside specifications for the meter in both upper and lower limits.
- In the forth case (Figure I.7), data is neither centered nor within the meter specification. It would be appropriate to seek a meter with more suitable specifications in these last three cases.

Presentation of Results

A number of basic techniques are used in analyzing and presenting data. These techniques assist in synthesizing large amounts of data to provide valuable information. Some of the more simple and common presentation techniques are briefly discussed below.

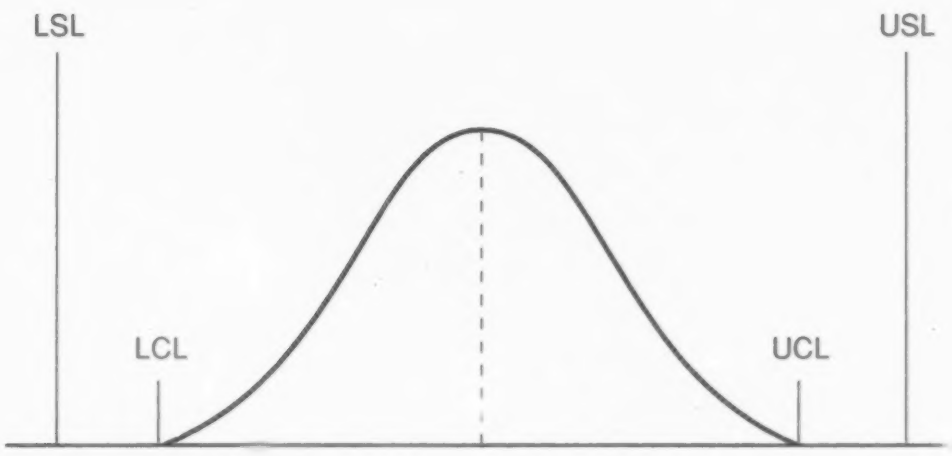

Figure I.4 Process in control and accurate

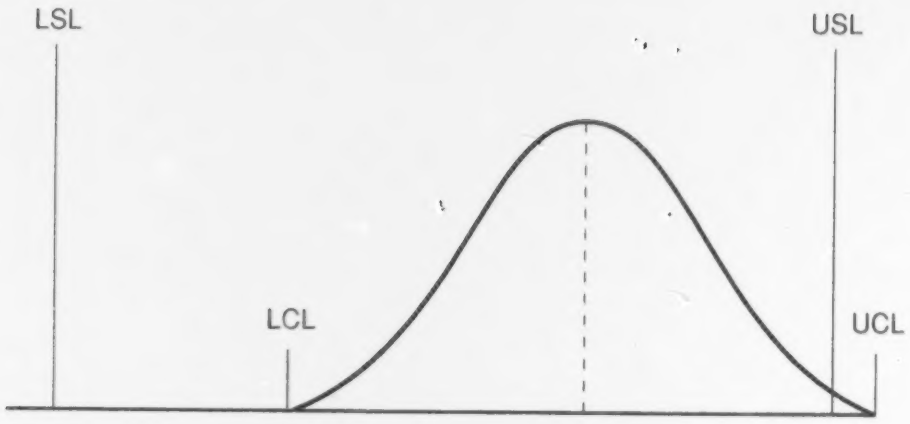

Figure I.5 Process is in control, but contains data shift

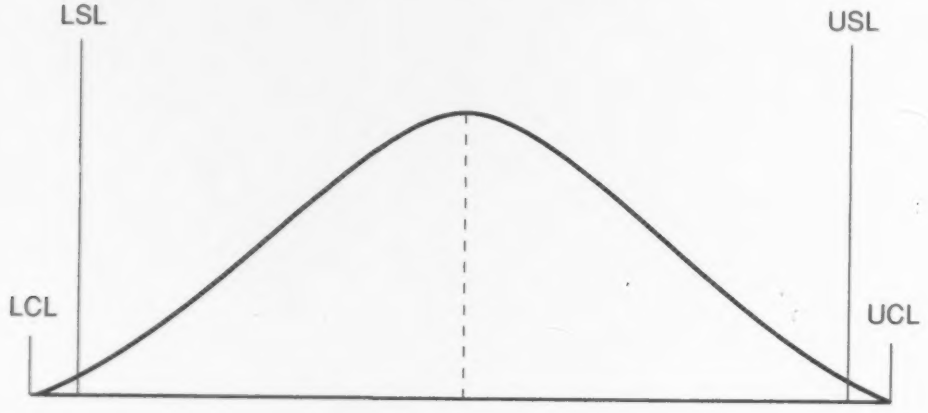

Figure I.6 Process is centered but not in control

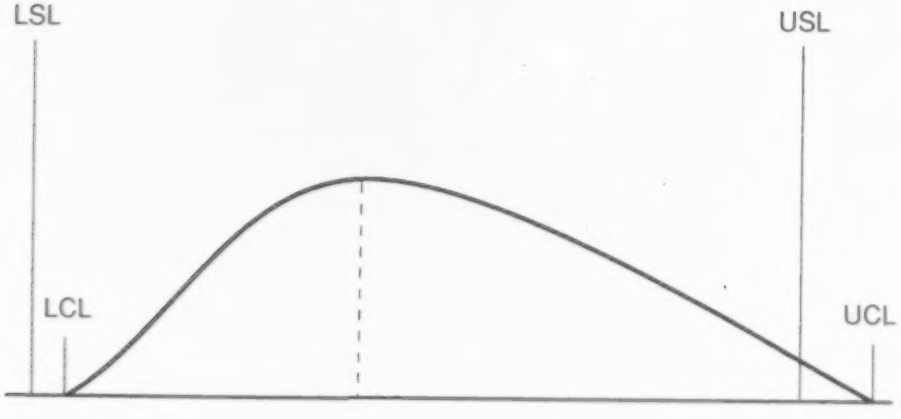

Figure I.7 Process is neither centered nor in control

Histograms

Histograms are a common and easily understood method of displaying large amounts of data and give an idea about the behavior of a process. Data are grouped into clusters, and each cluster is plotted relative to a value or "cause" on the "x" axis (Figure I.8). A data cluster may have any possible shape; however, for the process to be stable, the histogram will suggest a bell-shaped curve: the mode, mean, and median of the curve are the same and the mean value equally divides the data into two symmetrical groups of clusters. As illustrated in Figure I.8, clusters are typically plotted as bars on the graph.

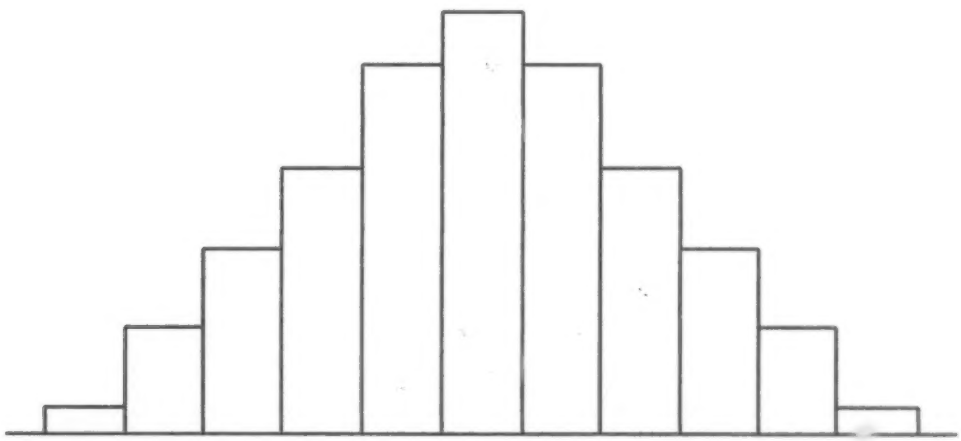

Figure I.8 Histogram

Pareto Diagram

A Pareto diagram is a graph that allows one to prioritize problems. It is a tool that helps "separate the wheat from the chaff." Vilfredo Pareto was an economist who concluded that in most situations only a few (approximately 20 percent) root causes solve most (about 80 percent) of the problem. This means that in most cases identifying a few important measurements will give us most of the information we need.

Therefore, a Pareto diagram can help analyze a problem from a fresh viewpoint, present issues in a ranked order, compare changes over time, or give a basis for determining cumulative effects over time. If one arranges data in the order of significance

by the number of occurrences from many to few, in most cases one can easily separate the vital few causes from the trivial many. (See Figure I.9)

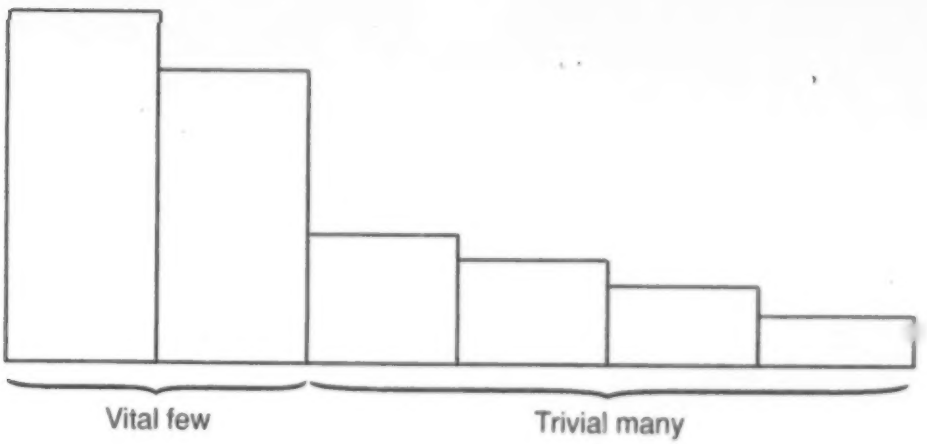

Figure I.9 Pareto diagram

Scatter Diagram

A scatter diagram is a method for determining if there is any correlation between two variables (Figure I.10). For instance, a scatter diagram would show that the amount of steam consumption for a facility is related to the number of heating degree-days. Knowing that a correlation exists can provide a clue to solving the problem.

To determine if there is a correlation between two variables, first collect the appropriate data points. Then plot the data points on a graph. Finally, examine the data points visually to determine if there is a relation between the two variables. The correlation between two variables can be positive, negative, or zero. Positive correlation means that when one variable increases, so will the other (e.g., as the number of heating degree-days increase, the amount of steam consumption will also increase). Negative correlation implies if one variable increases, the other variable will decrease (e.g., as the load of an electrical motor increases, the power factor decreases). Zero correlation means there is no relationship between the two variables.

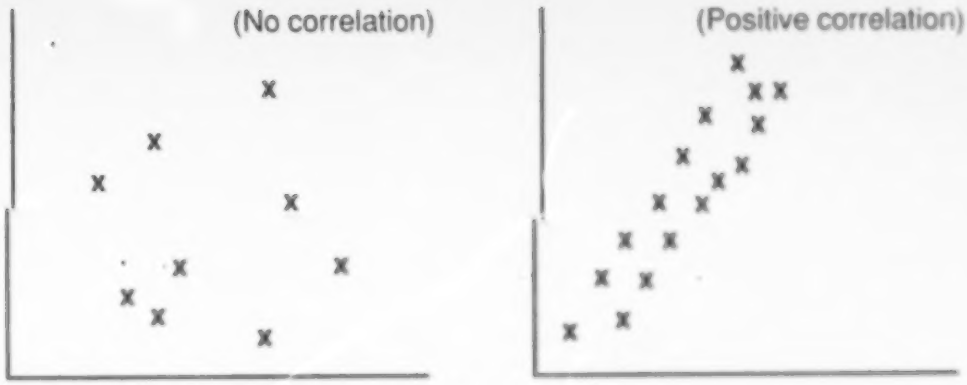

Figure I.10 Scatter diagram

If the data points are closely packed along a contour, the correlation is strong. It is important to mention that the correlation between two related variables does not have to be linear. The relationship can be quadratic, cubic, etc. For instance, the correlation between the speed of a centrifugal motor and the flow rate is quadratic. Similarly, the relationship between the flow rate and the power consumption of a centrifugal motor is cubic.

appendix II

Measurement Reliability

Measurement reliability is the assurance that the numerical quantity stated is the true representation of the actual value. To better appreciate measurement reliability, it is important to explain the factors that affect this concept:

- precision
- accuracy
- significant figures
- measurement error

Precision and Accuracy

The precision of a measurement relates to how often a measure can consistently be reproduced. The accuracy of a measurement is how close the measured value is to the "true" value. A measurement can be precise but not be accurate. This means precision does not necessarily imply accuracy. However, for accurate measurement, precision is required. Put another way, precision is a prerequisite for determining if a measurement is accurate, but does not guarantee its accuracy by itself.

The level of accuracy of measurement and the cost of measurement are inversely related. At higher and higher levels of accuracy, the cost increases at a disproportionately higher rate.

The following four scenarios will help illustrate the concepts of precision and accuracy. In each scenario, the current of a fully loaded electric motor is measured using four different ammeters. The current value is recorded after taking a series of measurements, and the resulting data are plotted as a normal distribution and compared with the true value.

- *Scenario one.* All of the data points are tightly clustered around the true value. This implies that ammeter # 1 is both precise *and* accurate (Figure II.1).
- *Scenario two.* Again the data points are all closely clustered together, which implies that ammeter # 2's readings are precise. However, most of the values are not close to the true

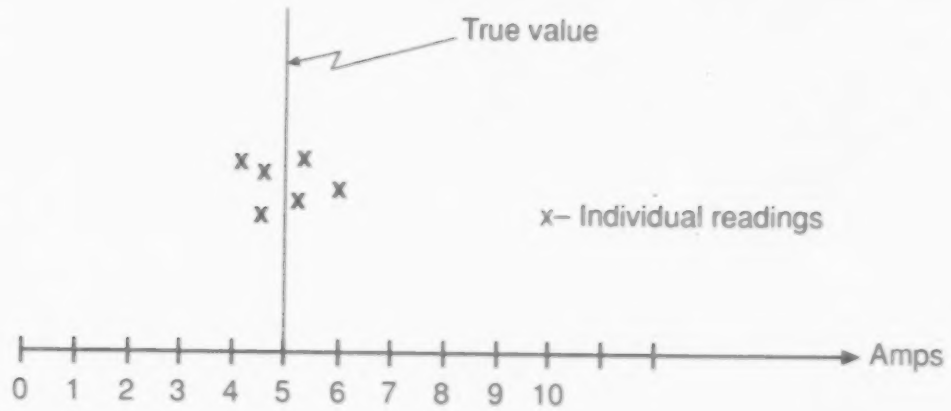

Figure II.1 Precise and accurate

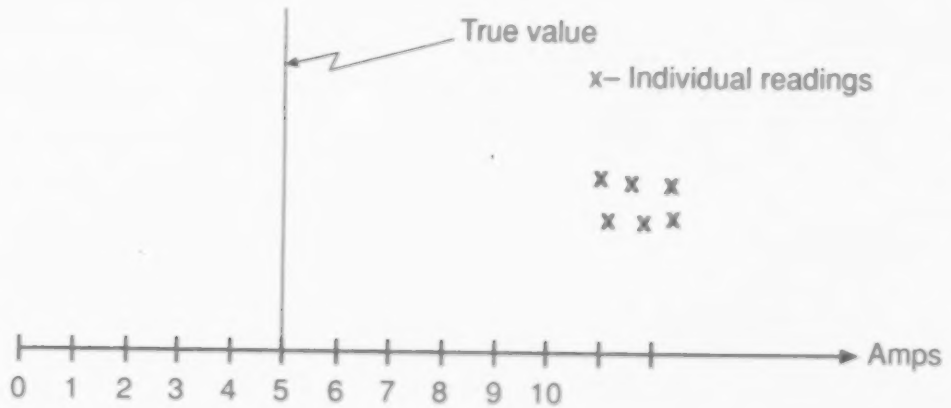

Figure II.2 Precise and not accurate

value, which suggests that the meter is not accurate (Figure II.2). (There is probably a drift problem with this ammeter.)

- *Scenario three.* Here data points are widely scattered, but the average of the value is close to the true reading. This implies that ammeter # 3 is accurate but not precise (Figure II.3).
- *Scenario four.* In this case, the data points are widely scattered and the average of these values differs from the true value. Therefore, ammeter # 4 is neither accurate nor precise (Figure II.4).

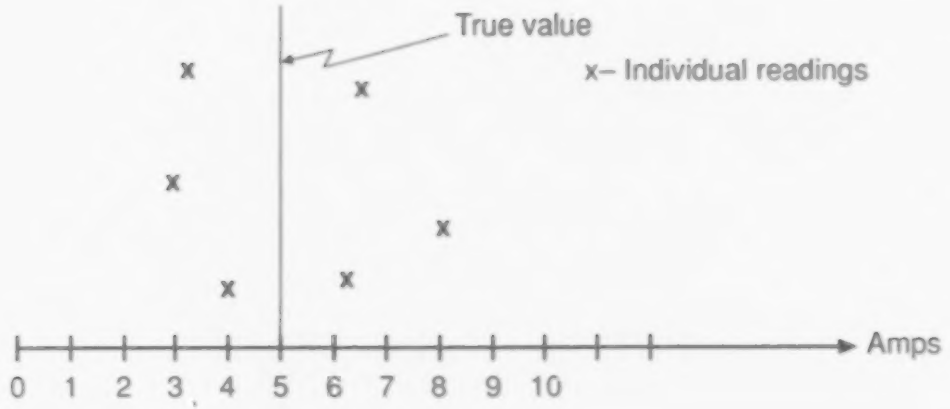

Figure II.3 Not precise but accurate

Significant Figures

Significant figures relate to the number of numerical digits a particular data point has. For instance, if the current of electrical equipment is reported as 25 amperes, it means the measurement has two significant figures. Moreover, it also means that the actual measure is somewhere between 24.5 and 25.5 amperes. Similarly, if the measurement is 25.0 amperes, the reading has three significant figures, and the actual reading is between 24.95 and 25.05 amperes.

As you can see, there is a direct correlation between the number of significant figures and the precision of a measurement. In other words, for a more precise measurement, one

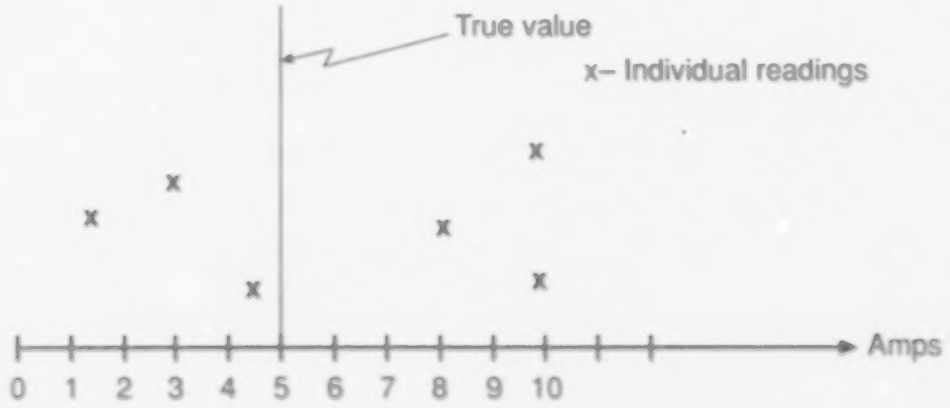

Figure II.4 Not precise or accurate

needs more significant figures, and conversely more significant figures imply higher precision.

Measurement Error

The difference between the true value and a measured value is called measurement error. Understanding errors is the first task in reducing them. Errors are mainly classified into two categories: absolute and relative.

Absolute error refers to situations where the value of the measurement error remains constant regardless of the magnitude of the reading. For instance, if we have a voltmeter that is off by 5 volts, when we measure 110 volts, 208 volts, or 480 volts, the absolute error is 5 volts in each case.

Relative error is absolute error divided by the measured value. For example, the relative errors for the above three situations are 5/110 (4.5 %), 5/208 (2.4 %), and 5/480(1 %) respectively.

Measurement error is commonly classified in three major categories: gross, random, and systematic.

Gross Error

Gross error primarily deals with reading and recording data incorrectly. This includes reading the wrong scale, transposing the figures, or putting the decimal point in the wrong place. The main reasons for this type of error are carelessness and lack of proper training. Gross error can be minimized by

- exercising care in the collection and recording of data,
- repeating the measurement process several times,
- checking if the reading appears to be unreasonably large or small compared to the expected reading, and
- automating of the measurement process.

Random Error

Random errors do not follow a particular pattern, magnitude, or direction, and they happen by accident. They are very difficult to spot. Random errors may occur for a variety of reasons, but it is usually difficult to account for them. However, in most cases, random errors tend to increase or decrease the measured value an equal number of times so the resultant impact of the error is zero. This means that random errors can be, in effect, eliminated

or greatly reduced by repeating the measurement process several times.

Systematic Error

Systematic errors are present because of one or more structural flaws in the measurement process. Repeating the measurement process does not eliminate systematic error. Systematic error can be divided into two main subgroups: mathematical error and physical error.

Mathematical error is associated with the size of the increments on the scale of the measuring device. For instance, measuring current with an electromechanical ammeter with a scale marked every 5 amperes will have a higher probability of error than an ammeter with a scale marked every 0.5 amperes.

Physical error can be due to a faulty meter, bad installation, calibration drift, environmental factors, etc. The source of physical error can be instrumental, human, or natural.

- Instrumental error is due to any meter malfunction or imperfections. This could be due to meter drift, misalignment of mechanical parts, poor design, or faulty construction. Instrument error arises in two situations. First there may be a shortcoming in the meter's capability due to calibration drift, faulty meter element, or the unit technology. The second source of instrumentation error is misuse of a meter or cases in which the presence of the meter loads the circuit to a point where circuit conditions change. Adverse environmental conditions, such as high humidity or large temperature fluctuations, may also be a source of instrument error.
- Human error refers to the limitations of our perception. For example, the observer can be a source of physical error for analog meters. When the reading is between two marks, some individuals tend to round the reading up while others round it down. Some individuals may look at the meter from an oblique angle instead of correctly looking at it head on. Taking multiple readings, appropriate training, and more careful observation all help to reduce human error. The advent of more digital technology and the ongoing proliferation of automation also will significantly reduce the opportunity for human error.

- Natural error is associated with inaccuracies in metering devices caused by ambient conditions such as humidity, temperature, and pressure.

Error Propagation

When we combine a number of different measurements (such as adding the energy consumption of several individual buildings), any error in the individual readings will also be contained in the total reading. The error of the combined measurement is related to the error of individual ones. This phenomenon is called error propagation. Error propagation is an important factor that should be considered when consolidating several measures using arithmetical operations such as addition, subtraction, multiplication, and division. To illustrate this let us look at the following example:

> Assume that the annual steam consumption of three residence halls is measured with individual meters each with an inherent error of 5 percent. The error of the consolidated heating consumption is actually 8.7 percent as shown below:
>
> Et = sqrt ((E1 x E1) + (E2 x E2) + (E3 x E3))
> = sqrt (25 + 25 + 25) = sqrt (75) = 8.7

The error of the combined measurement will always be higher than the largest individual error.

Techniques for Reducing Errors

Understanding error types and sources of errors is the first step in improving measurement reliability. After narrowing down the type of error based on the discussions above, appropriate measures can be taken. For instance, if the error is random, then repeating the measurement several times is necessary. On the other hand, if the measurement instrument is malfunctioning or misaligned, the instrument must be repaired or replaced.

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